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RESEARCH MEMORANDUM

INVESTIGATION OF AN ON-OFF INLET SHOCK-POSITION
CONTROL ON A 16-INCH RAM-JET ENGINE

By Fred A. Wilcox, Eugene Perchonok
and Donald P. Hearth

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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INVESTIGATION OF AN ON-OFF INLET SHOCK-POSITION CONTROL ON A 16-INCH RAM-JET ENGINE

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SUMMARY

A shock-positioning control was investigated on a 16-inch ram-jet engine at Mach numbers from 1.5 to 2.16 and angles of attack to 10° in the 8- by 6-foot supersonic wind tunnel. The static-pressure rise across the inlet normal shock was utilized in setting the diffuser at its critical condition. A simple pressure-capsule sensing element was combined with an on-off fuel-flow actuating system; and successful operation was obtained during rapid changes of angle of attack, stream Mach number, and exit nozzle throat area. In addition, the control restored the engine to the desired condition from manually displaced operation in both the subcritical and supercritical inlet flow regions.

Satisfactory prediction of the dynamic operation of the control was obtained by treating the system as having pure dead time.

INTRODUCTION

One purpose of a ram-jet fuel control system for a fixed-geometry engine is to regulate the diffuser flow conditions in a manner such as to match engine operation to the desired flight plan. Scheduled control of fuel-air ratio (refs. 1 and 2), while maintaining a desired fuel flow, may not provide accurate monitoring of engine thrust nor necessarily set the desired inlet operating condition. This is because variations in combustion efficiency are not fed back into this type of control.

Since variations in combustion efficiency directly affect the operating point of the diffuser, controls which regulate the fuel flow to give some desired diffuser operating condition more completely satisfy engine control requirements (refs. 3 to 5). The diffuser operating point may be determined from the position of the diffuser normal shock. By utilizing the large static-pressure rise across the normal shock, its location can generally be determined; and by varying the engine fuel flow, the shock may be positioned to maintain the desired operating point. Use is made of such a shock-positioning principle in the control of reference 3 as a limiter to prevent operation of the engine at too high a fuel flow.

A preliminary survey of an investigation of several control systems, including shock-positioning controls, on a 16-inch ram-jet engine (see ref. 6) is given in reference 7. The present report presents a detailed discussion of the steady-state and transient results obtained with a simple on-off shock-positioning control system designed to provide critical diffuser operation. 3438

SYMBOLS

The following symbols are used in this report:

A area, sq ft

a_t total amplitude of fuel-flow oscillation, lb fuel/hr

b width of dead band, lb fuel/hr

C_{F-D} propulsive-thrust coefficient, $\frac{F - D}{q_0 A_{max}}$

c maximum deviation of fuel flow above upper limit of dead band, lb/hr

d maximum deviation of fuel flow below lower limit of dead band, lb/hr

$\frac{dW_f}{dt}$ rate of change of fuel flow, (lb/hr)/sec

E_{max} maximum control error, lb fuel/hr

e amount of fuel-flow change by control during transient time, lb/hr

$F-D$ propulsive thrust, lb

f frequency of oscillation, cycles/sec

g acceleration due to gravity, 32.2 ft/sec^2

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M	Mach number
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
q	dynamic pressure, $\gamma p M^2/2$, lb/sq ft
R	gas constant for air, 53.3 ft-lb/(lb)($^{\circ}$R)
sfc	specific fuel consumption, $W_f/(F - D)$, (lb/hr)/lb
Δt	system dead time, sec
t_r	control response time, seconds to make full change in fuel flow
t_t	transient time, seconds to make change of imposed variable
V_1	voltage from pressure switch
V_2	voltage from controller
W_f	fuel flow, lb/hr
ΔW_f	change in fuel flow required by imposed transient, lb/hr
α	angle of attack, deg
γ	ratio of specific heats
δ	total pressure divided by NACA standard sea-level static pressure
η_b	combustion efficiency
θ	total temperature divided by NACA standard sea-level static temperature
φ	angle of yaw, deg

Subscripts:

av	average
max	maximum
x	air-flow measuring station in diffuser
0	free stream

1 reference station on spike

2 shock-sensing station

3 combustion-chamber inlet

APPARATUS AND PROCEDURE

The installation of the 16-inch ram-jet engine in the 8- by 6-foot supersonic wind tunnel is shown in figure 1. The engine was supported by a pivoted strut actuated by an air cylinder to provide nearly linear changes in angle of attack from zero to 10° in about 1 second. By using the inclined-plate technique of reference 8, the Mach number at the inlet could be changed from 1.70 to 1.90 and from 1.98 to 2.16 in about 0.5 second. The Mach number was increased by taking the engine with the plate attached from zero to about 5° angle of attack with the tunnel Mach number held fixed. Changes in the exit nozzle throat area of 21 percent were made in about 0.1 second by an air-actuated water-cooled tail plug.

The engine was the same as that reported in reference 6; the fuel used was MIL-F-5624B, amendment 1, grade JP-4. The diffuser was designed to have the oblique shock generated by the 25° half-angle cone fall slightly ahead of the cowl lip at M_0 of 1.8. Variation in the diffuser flow area is given in figure 2. A slight internal contraction occurred about 2 inches inside the cowl lip, preventing the inlet from swallowing the normal shock at Mach numbers below 1.78.

The locations of pressure orifices (1/16 inch in diam.) used for the control are shown in figure 2. Pressure orifice p_1 was used as a reference and was located on the horizontal center line 1 inch behind the tip of the spike. The orifice used to sense the position of the normal shock p_2 was located on the centerbody horizontal center line in the plane of the cowl lip. Alternate locations of the shock-sensing orifice were 1/2 and 6 inches inside the cowl lip on both the top and bottom of the cowl.

A can combustor with dual upstream injection was employed. Fuel flow to the inner or primary fuel manifold was set manually to give a ratio of primary fuel to engine air of about 0.015 for all operating conditions. The fuel to the outer or secondary manifold was controlled by the servo-operated fuel valve described in reference 7. The valve was designed to give a linear variation in fuel flow with imposed d-c voltage.

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Control of the voltage signal to the throttle was provided by a simple on-off pressure switch (fig. 3). The switch has a rubber diaphram and two contact points. Differential pressure across the diaphram causes it to stretch and make contact with circuits to either decrease or increase engine fuel flow. Adjusting screws permit setting the switch to make contact at the desired differential pressure. Internal volume of the switch was about 2 cubic centimeters. The switch was connected to the pressure orifices with 12 inches of 1/16-inch-I.D. tubing. The time required for the switch to make contact when a step change in pressure was applied was 0.02 second. This time is termed the switch "dead time."

For the steady-state data, an automatic digital pressure recorder was utilized. Fuel flows were obtained with rotameters. For the transient data, pressures were measured by dynamic pickups; angle-of-attack and exit plug positions were measured by slide-wire position indicators; and all were recorded with oscillographs. Fuel flows for the transient data were obtained from the pressure variations measured across the fuel manifold. Two oscillographs were used, one a pen type for visual observation of control action and the other a more accurate optical type. For ease of interpretation, the traces presented in this report are from the pen-type recorder.

OPERATION OF CONTROL

Operation of the control is illustrated schematically in figure 4. When the engine fuel flow is too low (fig. 4(a)), the normal shock is situated inside the cowl. Pressures on both sides of the pressure switch are approximately equal and the contacts are set so that the diaphram closes the circuit to increase the fuel flow. The corresponding increase in heat release forces the normal shock forward, yielding the situation illustrated in figure 4(b). With the normal shock located between the two orifices, the downstream static pressure is much higher than the upstream value because of the static-pressure rise across the shock. The high differential pressure across the switch then closes a circuit to decrease the fuel flow.

The block diagram for the control system is shown in figure 5(a). A differential pressure signal from the engine inlet is fed through the pressure switch (fig. 5(b)) to a controller (fig. 5(c)). The controller signals the fuel throttle, which then varies the fuel flow W_f to the engine in a linear manner. When the diaphram of the pressure switch floats between the two contact points, the control is in its "dead band," and the fuel flow remains fixed. At pressure differentials below 94 pounds per square foot, the diaphram makes contact with the battery sending a $+V_1$ to the controller, which will then cause the fuel flow to increase. At pressure differentials above 200 pounds per square foot, the pressure switch sends a minus voltage signal to the controller and the fuel flow will decrease.

The manner in which the controller operates to vary the voltage signal to the throttle is shown in figure 5(c). The voltage from the pressure switch charges a condenser in a series resistance-capacitance circuit. By use of a large condenser a nearly linear rate of change of voltage across the condenser is obtained. This voltage was fed through an amplifier to operate the servo throttle. The RC circuit was variable to permit selection of the desired rate of change of fuel flow. 3438

RESULTS AND DISCUSSION

Sensing pressures used to actuate the control are presented in figure 6 for Mach numbers from 1.5 to 2.16 at angles of attack to 10°. These data are for manually set engine operating conditions. The static-pressure coefficient presented is the difference between the sensing and the reference pressure divided by the free-stream static pressure. The dashed lines on the figure show the values of the static-pressure coefficient at which the pressure switch operated. Only one setting of the switch is represented, and the shift in the operating line with Mach number is due to a concurrent change in altitude from 27,500 to 43,000 feet. The data indicate that for the switch setting used the control should function at all Mach numbers except 1.5, where the normal shock could not be swallowed because of inlet internal contraction. Ideally, the static-pressure coefficient should be zero for supercritical engine operation and should rise instantaneously to the theoretical value as the combustion-chamber-inlet Mach number is lowered below the critical value. Deviations of the static-pressure coefficient from the theoretical are attributed to the effect of boundary layer along the spike surface. Separation of the boundary layer behind the normal shock was observed at Mach 1.98 by means of schlieren photographs and is believed responsible for the shift of the controlled point to a subcritical value at this Mach number.

For convenience in relating the data presented herein as a function of the combustion-chamber-inlet Mach number M_3 to fuel flow, the variation of the fuel-flow parameter $\frac{W_f\sqrt{\theta_3}}{\delta_3}$ and M_3 is given in figure 7 for various values of combustion efficiency.

Engine performance set by the control is shown in figure 8 on the performance curves presented in reference 6. For all stream Mach numbers the controlled diffuser-exit Mach number is in agreement with the values expected from figure 6. Due to the inherent hunting operation of an on-off system, the data points represent some oscillation of the engine fuel flow. Time integration of the steady-state engine performance over the conditions imposed by these fuel-flow oscillations results in a computed engine performance less than that observed experimentally and given in figure 8. It appears that a detailed study of ram-jet-engine dynamics is in order to more fully explain engine performance under an oscillating fuel flow.

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At Mach 1.79 (fig. 8(a)), the control set engine operation close to critical at angles of attack to 10°. At Mach 1.98 (fig. 8(b)), the control set a specific fuel consumption which was nearly minimum for the engine. However, the inlet operating point was somewhat subcritical and a slight diffuser buzz was obtained. This resulted in burner blow-out at 10° angle of attack but not at 5°. At Mach 2.16 (fig. 8(c)), the control set an operating point close to critical. Operation at this Mach number was restricted to zero angle of attack because of the test technique.

Since the control set a slightly subcritical operating point at Mach 1.98, data from a previous investigation (ref. 9) were examined for improved pressure-sensing locations. Data are shown in figure 9 for pressure taps located along the cowl inner surface. Because of the area variation of the diffuser, little difference was found between points 1/2 inch to 6 inches downstream of the lip. Because the cowl-lip angle is lower than the flow angle, additional compression is achieved and the local static pressure is greater than the corresponding values on the centerbody. Therefore, sensing pressure p_2 on the inner surface of the cowl instead of on the centerbody will result in control closer to the critical point at all Mach numbers investigated. In addition, the abrupt pressure rise at the cowl orifices for Mach numbers above 1.8 will permit M_3 control closer to the critical point over a greater altitude range than obtainable with the sensing orifice position used.

Pressure data were obtained for the cowl orifice location under simulated conditions of yaw. Wall static data for $\pm 3^{\circ}$ of yaw are shown in figures 10(a) to (c) for a position 6 inches from the cowl lip. Reasonably good control can be obtained at this condition by proper setting of the pressure switch. At 6° of yaw (figs. 10(d) to (f)), it would be difficult to find a pressure-switch setting which will give good control over the complete Mach number range.

An example of the oscillation of the on-off control system at Mach 1.98 is shown by the oscillograph trace in figure 11. A rate of change of fuel flow of 3690 pounds per hour per second resulted in a total fuel-flow oscillation of 432 pounds per hour at a frequency of 4.7 cycles per second. The total amplitude of oscillation of the diffuser-exit total pressure was 185 pounds per square foot or 6.4 percent of the total pressure. The oscillation of the voltage from the controller and fuel pressure at the spray nozzles was of the triangular shape shown in the appendix for a system having a dead time and no dead band. The dead-band setting of the pressure switch results in a very narrow dead band of M_3 as shown on figure 6. This, in turn, results in a very narrow fuel-flow dead band.

Preliminary engine dynamic data (ref. 7) show that, when a step change in fuel flow is imposed, there is a period from 0.02 to 0.05 second during which the engine does not respond. At critical conditions, the value of this engine dead time was about 0.025 second. The effective dead time of the fuel system was approximately 0.01 second, and the measured pressure-switch dead time was 0.02 second. By adding the dead times of the components, the system dead time is determined as 0.055 second. The observed frequency of oscillation of the control was 4.5 ±0.8 cycles per second for all conditions investigated, the average being 4.5. This latter value is identical with the frequency predicted by substituting a system dead time of 0.055 second into equation (1) of the appendix. 3438

Theoretical amplitude of fuel flow oscillation was calculated from equation (3) of the appendix using the above value of system dead time and is presented in figure 12 for various rates of change of fuel flow. Data read from oscillograph traces for the various operating conditions agree reasonably well with the predicted values. The amplitude of oscillation is seen to increase linearly with the rate of change of fuel flow.

It is indicated in reference 7 that following the engine dead time an additional time, termed "lead-lag," is sometimes required for the engine to reach equilibrium conditions. This lead-lag term which has a time constant varying from 0.1 to 0.4 second apparently had little effect on the operation of the on-off control since oscillation frequency and amplitude could be predicted assuming that the system has pure dead time.

Selection of the rate of change of fuel flow to be used with an on-off control must be a compromise between the tolerable steady-state oscillation and the allowable error imposed on the engine during a transient. To keep the steady-state oscillation amplitude low, the rate of change of fuel flow should be as low as possible (see eq. (2) or (3) in the appendix). To keep the error during the transient low, the rate of change of fuel flow should be sufficient to provide a response time close to the imposed transient time (eq. (6) and sketch 4 of appendix). Examples of various rates of change of fuel flow and their effect on the error and amplitude of fuel-flow oscillation are presented in figures 13 to 16.

Operation of the control when the angle of attack is changed from zero to 10° in 1.13 seconds is indicated in figure 13. Fuel flows listed on the figure are those to the secondary manifold. The final average fuel flow was 115 pounds per hour lower than the initial value. From equation (6) of the appendix, a rate of change of fuel flow of 107 pounds per hour per second is required for a response time equal to the transient time. The rate of change of fuel flow used for the transient was 742 pounds per hour per second, thus providing small error during the transient. The irregularities in the fuel pressure trace result from the high oscillograph gain setting necessitated by the small transient fuel-flow change.

Operation of the control during a change in Mach number from 1.98 to 2.16 in 0.58 second is shown in figure 14. The change in fuel flow was 225 pounds per hour and would have required a rate of change of fuel flow of 430 pounds per hour per second. Since a rate of change of 371 pounds per hour per second was used, it was estimated from equation (8) of the appendix that an error of 30 pounds per hour would result during the transient. After the transient, an oscillation of about 220 pounds per square foot in P_x was obtained. This is believed caused by the diffuser buzz occurring at the slightly subcritical operating point set by the control.

From consideration of the accelerating capabilities of the engine, it can be shown that, except for gusts, the change in Mach number in 0.58 second investigated herein is greater than that generally expected in flight. At Mach 1.98 the thrust-minus-drag coefficient at critical operation is 0.595 (ref. 6). Assuming a missile weight of 1500 pounds per square foot of frontal area to allow for fuel, pay load, and structure, the acceleration provided by the engine in level flight at Mach 2.0 would be 14 feet per second per second. The maximum steady full-power acceleration the missile could experience would be 14 + 32.2 or 46.2 feet per second per second if it were going straight down at full thrust. This would give a time required to accelerate from Mach 2 to 2.16 of 3.8 seconds or about $6\frac{1}{2}$ times longer than that obtained during the transient of figure 14. It should be pointed out that the change in Mach number indicated on this figure was not made at a constant altitude because of the technique used. The altitude increased from about 37,000 to 43,000 feet during the M_0 change, requiring a net reduction in fuel flow. This reduction in fuel flow was approximately equal in magnitude to the fuel-flow increase which would have been required had the Mach number change been made at constant altitude.

The operation of the control during transients occurring at a rate beyond its corrective ability was also studied. Figure 15(a) shows the operation of the control during a change in exit nozzle area from 0.96

to 0.76 square foot occurring in 0.11 second. The reduction in fuel flow required was 1125 pounds per hour or a rate of change of fuel flow of 20,500 pounds per hour per second. Since the rate of change used was 742 pounds per hour per second, the control response was inadequate and the diffuser went into the buzz region as can be seen from the diffuser-exit total-pressure trace. The maximum fuel-flow error estimated from equation (8) of the appendix was 1085 pounds per hour. Even if the rate of change of fuel flow were increased, it is not possible to reduce this error below 562 pounds per hour (see eq. (7) and sketch 4 of appendix) because the system dead time is so large a percentage of the transient time.

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During the period when the large error in fuel flow existed, the diffuser went into a buzz condition. This buzz was not of sufficient violence to blow out the burner, and after 1.54 seconds the control set the proper fuel flow. Response time estimated from equation (5) of the appendix is 1.57 seconds. Experience obtained with the control indicated that engine operating limits during control action are the same as the steady-state engine operating limits under manual control.

The operation of the control system when the exit area was restored from 0.76 to 0.96 square foot in 0.17 second is shown in figure 15(b). The diffuser went supercritical during the change, and the pressure recovery dropped from 0.915 to 0.82 before the restoring action of the control reestablished critical diffuser operation.

In figure 15(c) the rate of change of fuel flow was increased to 2450 pounds per hour per second, and the exit-area change from 0.96 to 0.80 square foot occurred in 0.09 second. The required change in fuel flow was 848 pounds per hour, which would have required a rate of change of 24,300 pounds per hour per second. The dW_f/dt value used was again low with the result that the diffuser went briefly into buzz. The pressure recovery dropped to 0.895 and reached an oscillation amplitude of 135 pounds per square foot for about a 0.1-second duration. The maximum error in fuel flow is estimated at 762 pounds per hour, and the lowest obtainable error would be 518 pounds per hour.

The action of the control in restoring manually displaced fuel flow is shown in figure 16 to demonstrate that satisfactory control action will be obtained if the diffuser is set either far supercritical or in violent subcritical buzz. In figure 16(a) the engine was manually set at a fuel flow giving operation at M_0 of 1.98, which was far supercritical. The rate of change of fuel flow used (7150 (lb/hr)/sec) gave a response of 0.265 second. From equation (5) of the appendix the theoretical response time was 0.19 second. The Δt term of the equation is zero for this case, since control action starts immediately upon release of the manual switch. The actual response time was greater than the theoretical value because of the observed fuel-system lag at the low fuel flow and the correspondingly low fuel pressure initially set.

Operation of the control to bring the engine back to the operating point despite a violent diffuser buzz is shown in figure 16(b). The fuel flow was set at a high value, which resulted in violent diffuser buzz at an amplitude of about 365 pounds per square foot. The theoretical response time for the rate of change (7150 (lb/hr)/sec) used was 0.14 second. Measured response time was 0.13 second, during which time the P_x oscillation dropped to 140 pounds per square foot, a condition resulting from a combination of the steady hunting of the fuel flow of about 800 pounds per hour and the slightly subcritical point set by the control.

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OTHER APPLICATIONS OF CONTROL

The shock-positioning-control applications discussed in both reference 7 and herein were made to fixed-geometry supersonic inlets. The same shock-positioning principles may be applied to inlets such as those required for turbojet installations having variable-geometry features. These features are used to efficiently match the air flow supplied by the inlet to that required by the engine. This matching can be done either by translating the engine spike forward to spill air supersonically or by spilling air through bypass doors located at the diffuser exit. In either case most efficient operation is obtained over a range of engine operating conditions with the inlet normal shock at the cowl lip. The control can be used for this application by having it operate the translating-spike or bypass-door mechanisms. Location of the sensing orifice on the inside surface of the cowl would be preferable for the translating-spike application as it would not move with the spike.

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CONCLUDING REMARKS

The principle of shock-position control has been demonstrated for a fixed-geometry ram-jet engine using a simple on-off control system. In general, the control operated at all conditions of stream Mach number and angle of attack at which the engine could be manually operated. Restoring action was obtained from either far subcritical or far supercritical conditions; and satisfactory control could be maintained during transients in free-stream Mach number, angle of attack, and exit nozzle throat area. Prediction of the control-system dynamic behavior can be made by treating the system as having pure dead time. Although applied to a fixed-geometry inlet, the same shock-positioning-control principle can be applied to inlets having variable-geometry features.

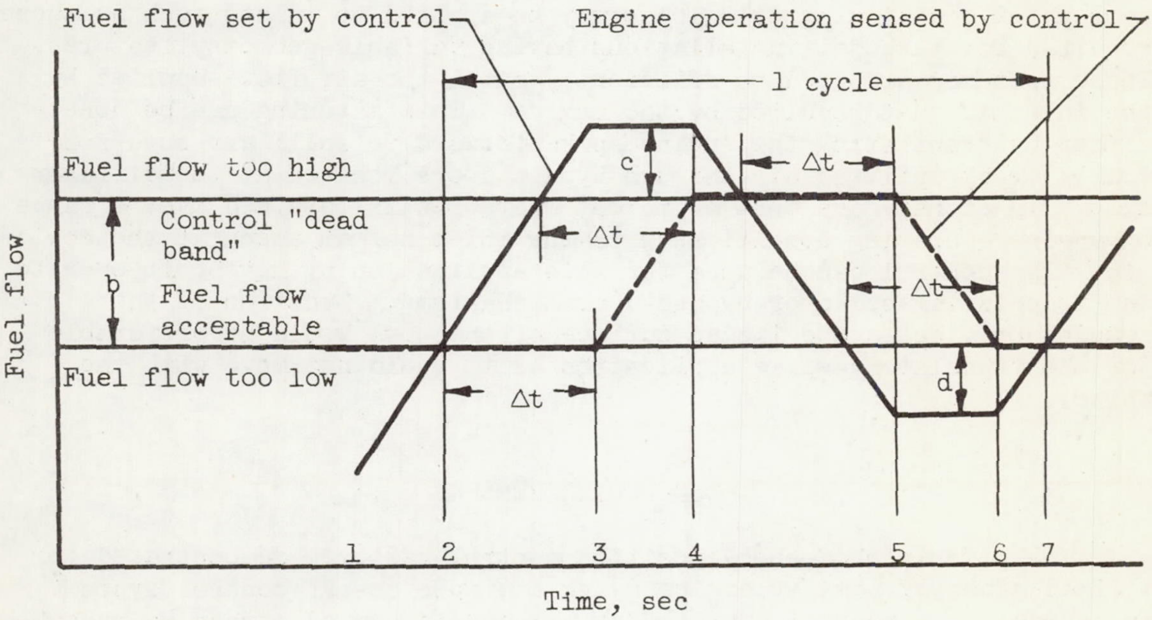
Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, September 16, 1954

APPENDIX - DYNAMIC BEHAVIOR OF ON-OFF CONTROL

WITH A SYSTEM HAVING PURE DEAD TIME

The system having pure dead time and a linear change in control action is a special case of the on-off controls given more general treatment in reference 10. It is assumed that the rate of change for increasing fuel flow is equal to the rate of change for decreasing flow. Also assumed is a constant value of "system dead time," that is, the length of time required for the control to sense the result of a change in engine fuel flow. 3438

Frequency of oscillation. - The steady hunting characteristics of an on-off control system having a linear change in fuel flow and pure dead time Δt are shown in the following sketch:



Sketch 1.

Included in the system is a "dead band," defined as the range of fuel flow for which no change in flow is asked for by the control. The solid line represents the fuel flow set by the control. The dashed line represents the condition of engine operation sensed by the control. The on-off control senses only that the fuel flow is too low, acceptable, or too high. Changes from one of these conditions to another are sensed after their occurrence at a time equal to the system dead time.

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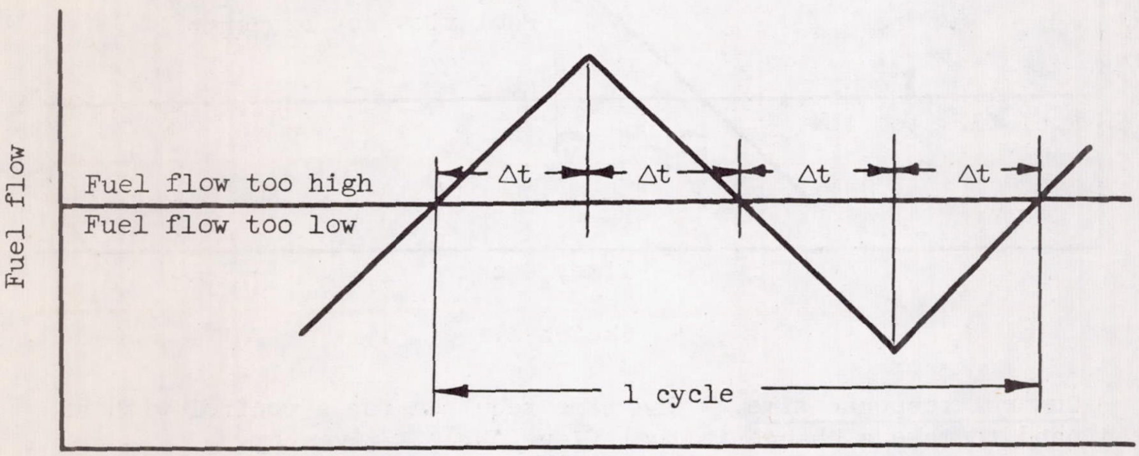
Starting at point 1, the engine fuel flow is too low and is being increased by the control. At point 2 the engine fuel flow reaches an acceptable value, but the control does not sense this until point 3 is reached. The control then stops changing the fuel flow. At point 4 the control senses that the fuel flow is too high and decreases it. The control action overshoots at point 5 as it did at point 3, and the cycle is completed at point 7. From the symmetrical nature of the diagram, the length of the cycle is $4\Delta t$. The frequency of oscillation is then given by

$$f = \frac{1}{4\Delta t} \tag{1}$$

Oscillation frequency is thus independent of the dead-band setting of the control. If the control has no dead band, its steady hunting action has a triangular wave shape as shown by the following sketch:



Sketch 2.

Amplitude of oscillation. - From sketch 1 the total amplitude of oscillation of fuel flow is given by

$$a_t = b + c + d$$

or

$$a_t = 2\Delta t \frac{dW_f}{dt} - b \tag{2}$$

If the system has no dead band, the total amplitude becomes

$$a_t = 2\Delta t \frac{dW_f}{dt} \tag{3}$$

For a system with a sufficiently wide dead band so that the control stops changing the fuel flow while the fuel flow is within the dead band, no periodic oscillation will occur. The width of the dead band for this condition is shown in sketch 3 and is given by

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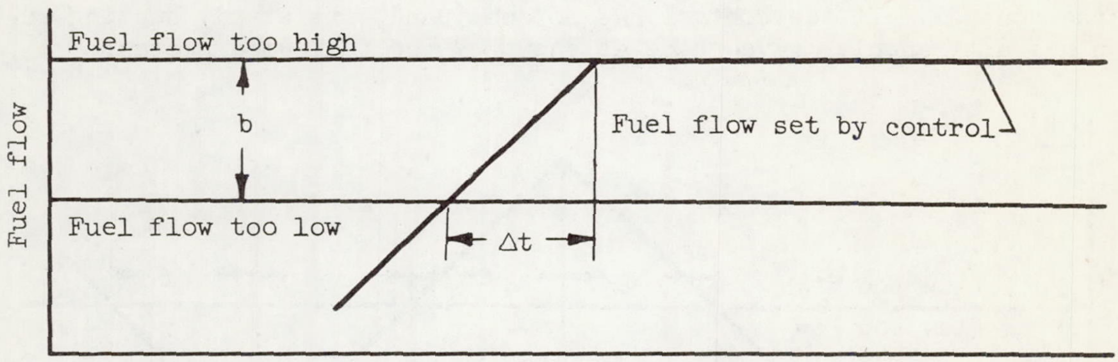
$$b \geqq \Delta t \frac{dW_f}{dt} \tag{4}$$



Sketch 3.

<u>Control response time</u>. - The time required for a control with no dead band to make a change in fuel flow ΔW_f is given by

$$t_r = \frac{\Delta W_f}{dW_f/dt} + \Delta t \tag{5}$$

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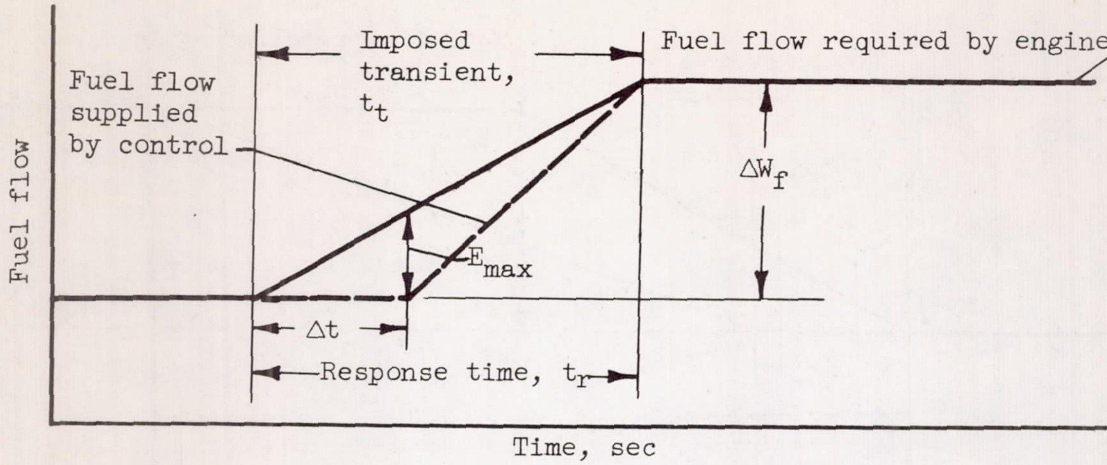
as can be seen from sketch 4.



Sketch 4.

The rate of change of fuel flow required to have a response time equal to the imposed transient time is given by

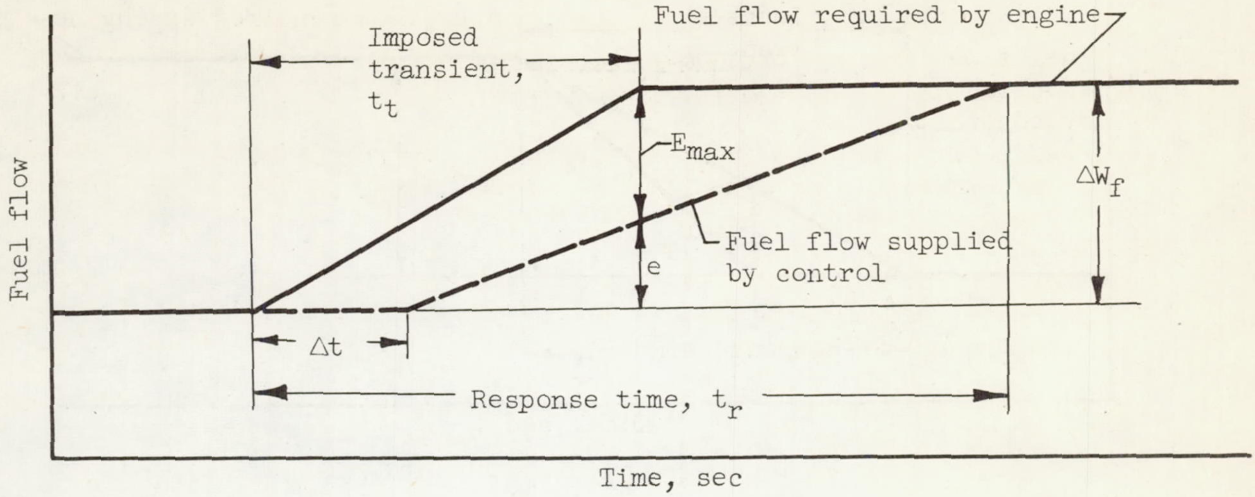
$$\frac{dW_f}{dt} = \frac{\Delta W_f}{t_t - \Delta t} \tag{6}$$

This will not result in zero error during the transient, however. The maximum error during the transient will depend on the severity of the transient and relative values of transient and system dead time. Maximum error for the case where response time is equal to or less than the imposed transient time is given by

$$E_{max} = \Delta W_f \frac{\Delta t}{t_t} \tag{7}$$

from sketch 4.

If the rate of change of fuel flow is lowered so that the response time is much greater than the imposed transient, the maximum error would occur at the end of the imposed transient as shown in sketch 5:



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Sketch 5.

The maximum error for this case is given by

$$E_{max} = \Delta W_f - \frac{dW_f}{dt}(t_t - \Delta t) \tag{8}$$

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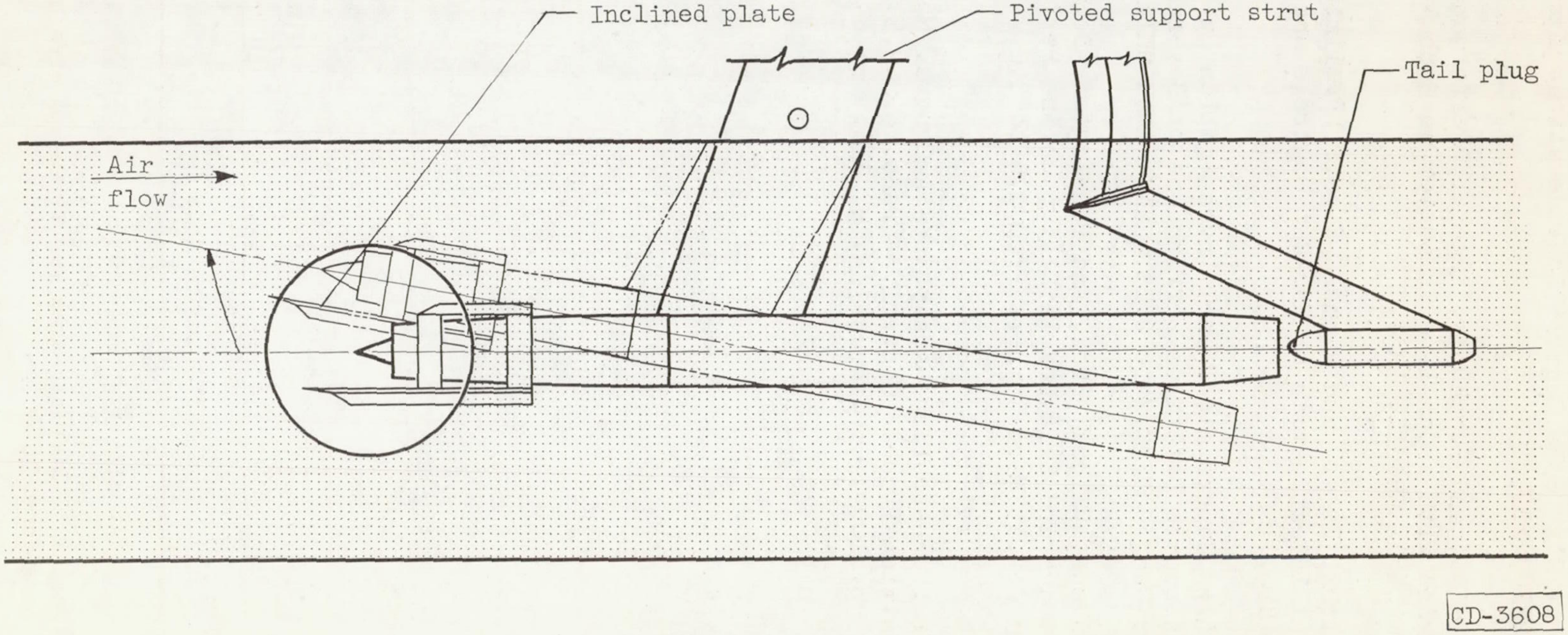

Figure 1. - Installation of 16-inch ram-jet engine in 8- by 6-foot supersonic wind tunnel.

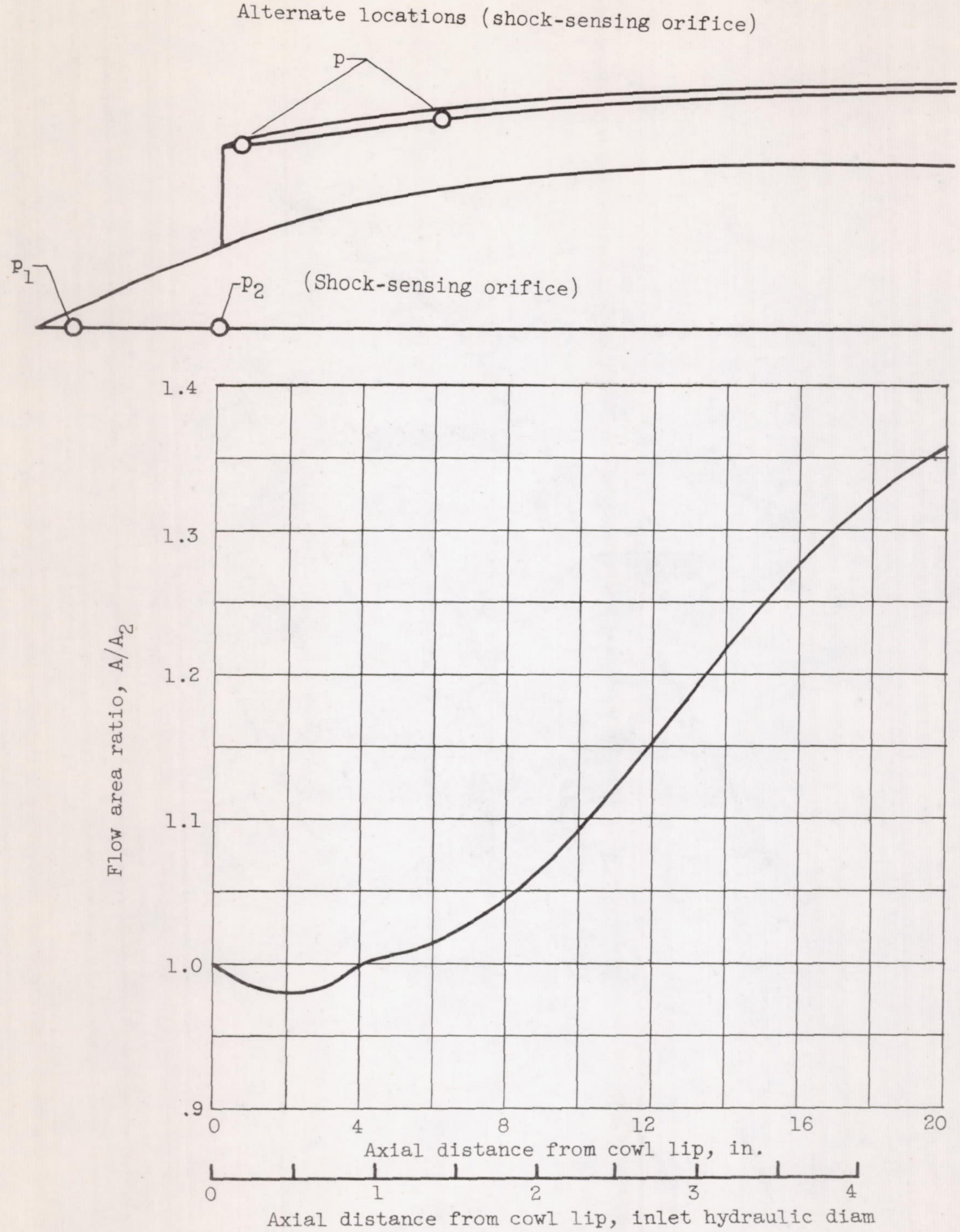

Figure 2. - Diffuser-area variation and pressure-orifice locations.

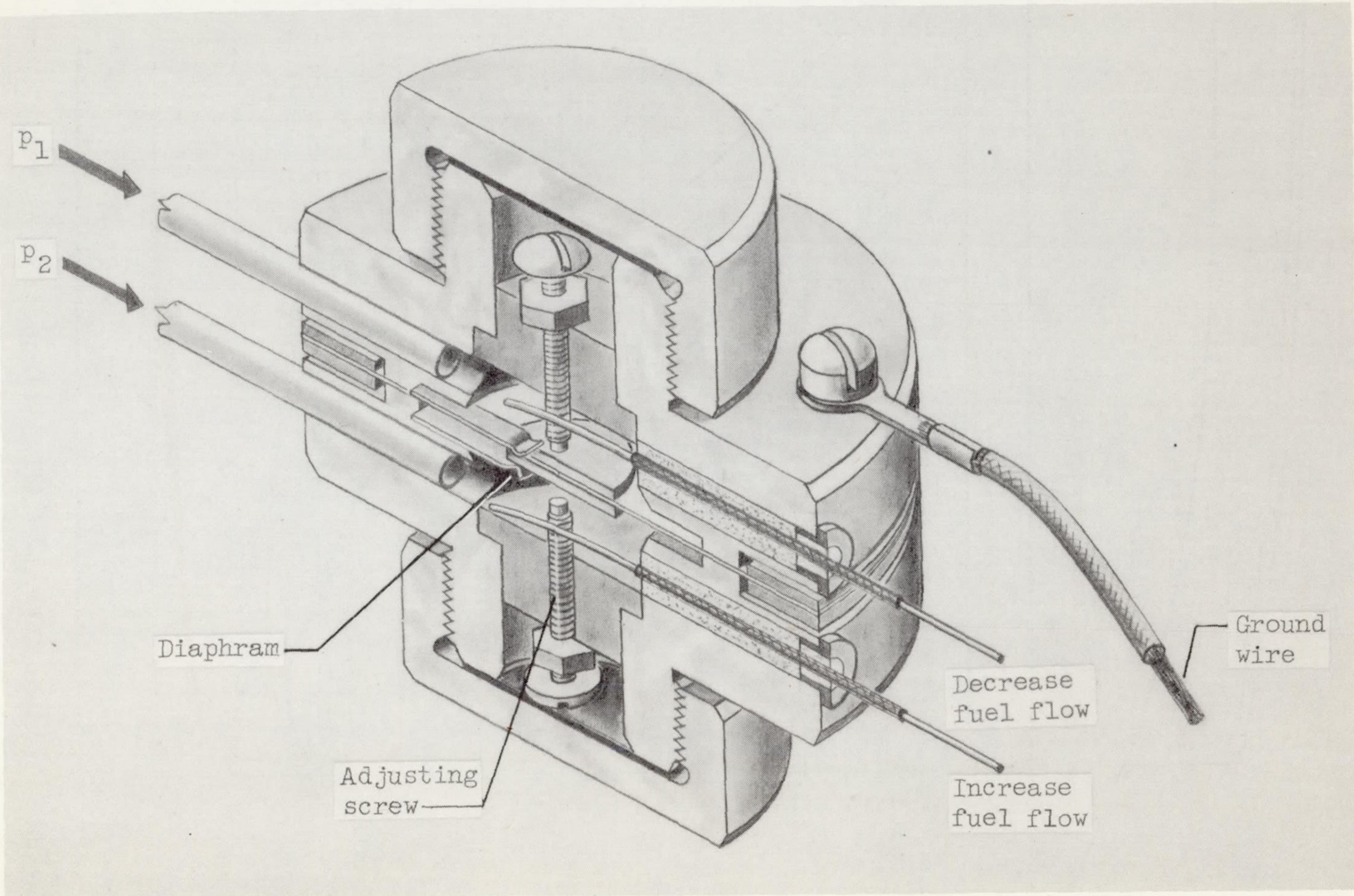

Figure 3. - Cut-away drawing of pressure switch. CD-3600

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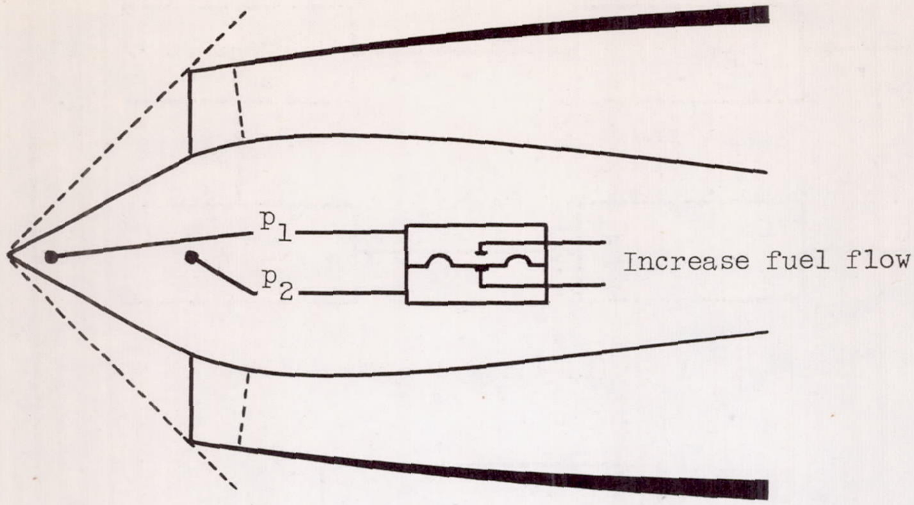
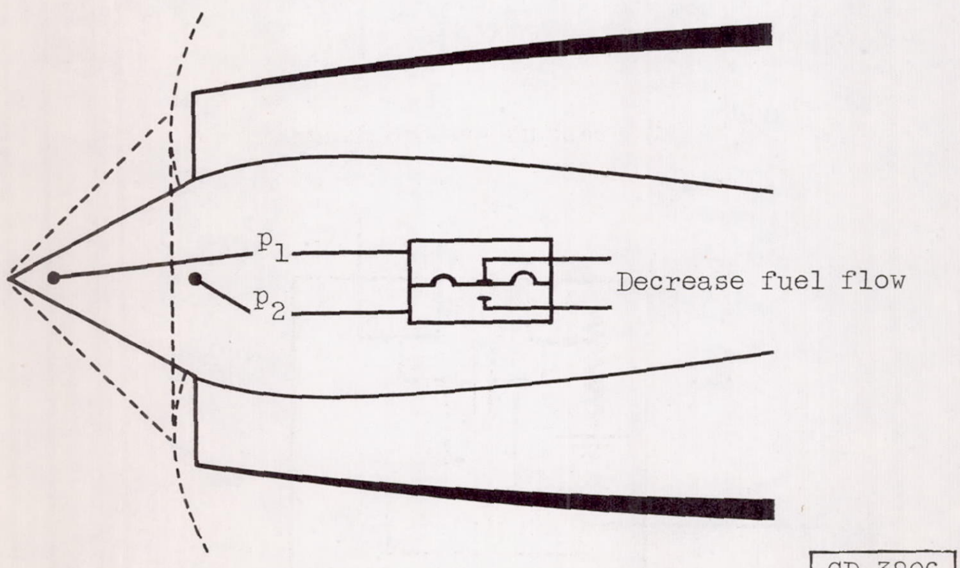


(a) Fuel flow too low, $p_1 \approx p_2$.



(b) Fuel flow too high, $p_2 > p_1$.

Figure 4. - Schematic diagram of operation of shock-positioning control designed to hold diffuser at critical.

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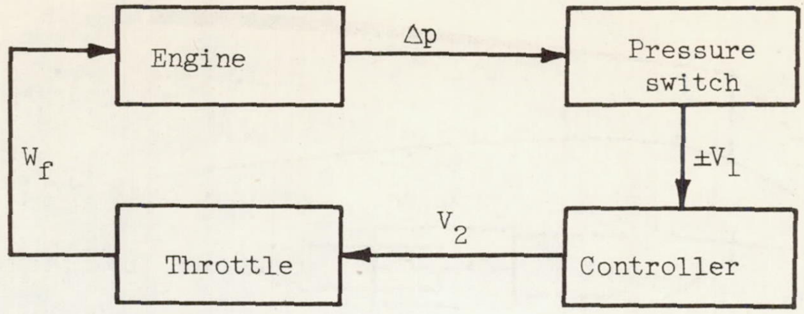
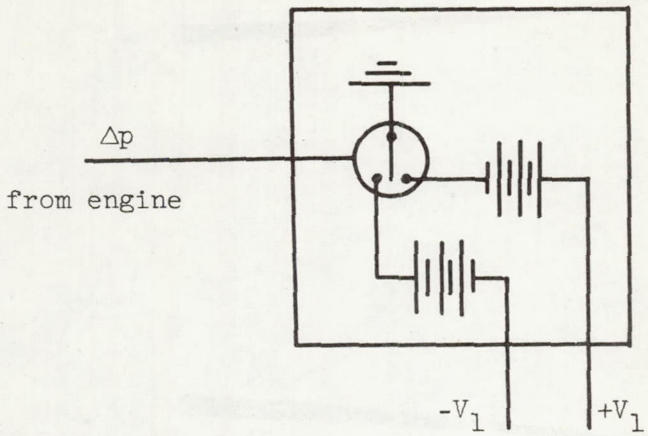
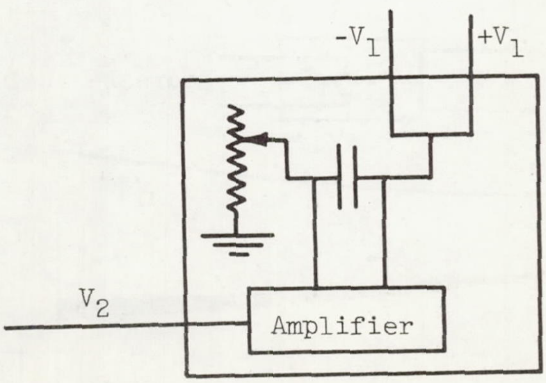


(a) Block diagram.



(b) Pressure-switch diagram.



(c) Controller diagram.

Figure 5. - Block, pressure switch, and controller diagrams.

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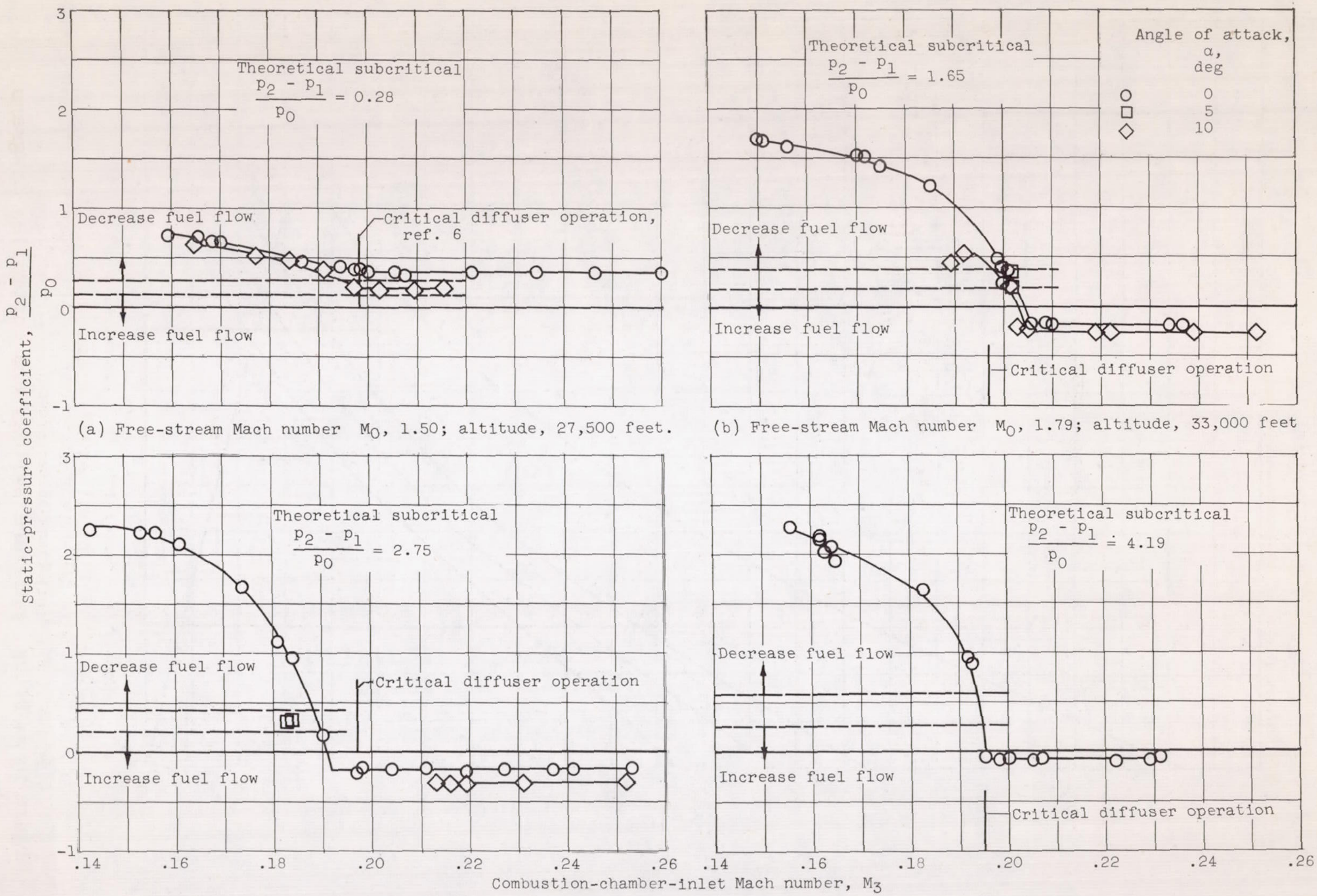

(a) Free-stream Mach number M_0, 1.50; altitude, 27,500 feet.

(b) Free-stream Mach number M_0, 1.79; altitude, 33,000 feet

(c) Free-stream Mach number M_0, 1.98; altitude, 37,000 feet.

(d) Free-stream Mach number M_0, 2.16; altitude, 43,000 feet.

Figure 6. - Sensing pressures on centerbody at cowl lip. Zero angle of yaw.

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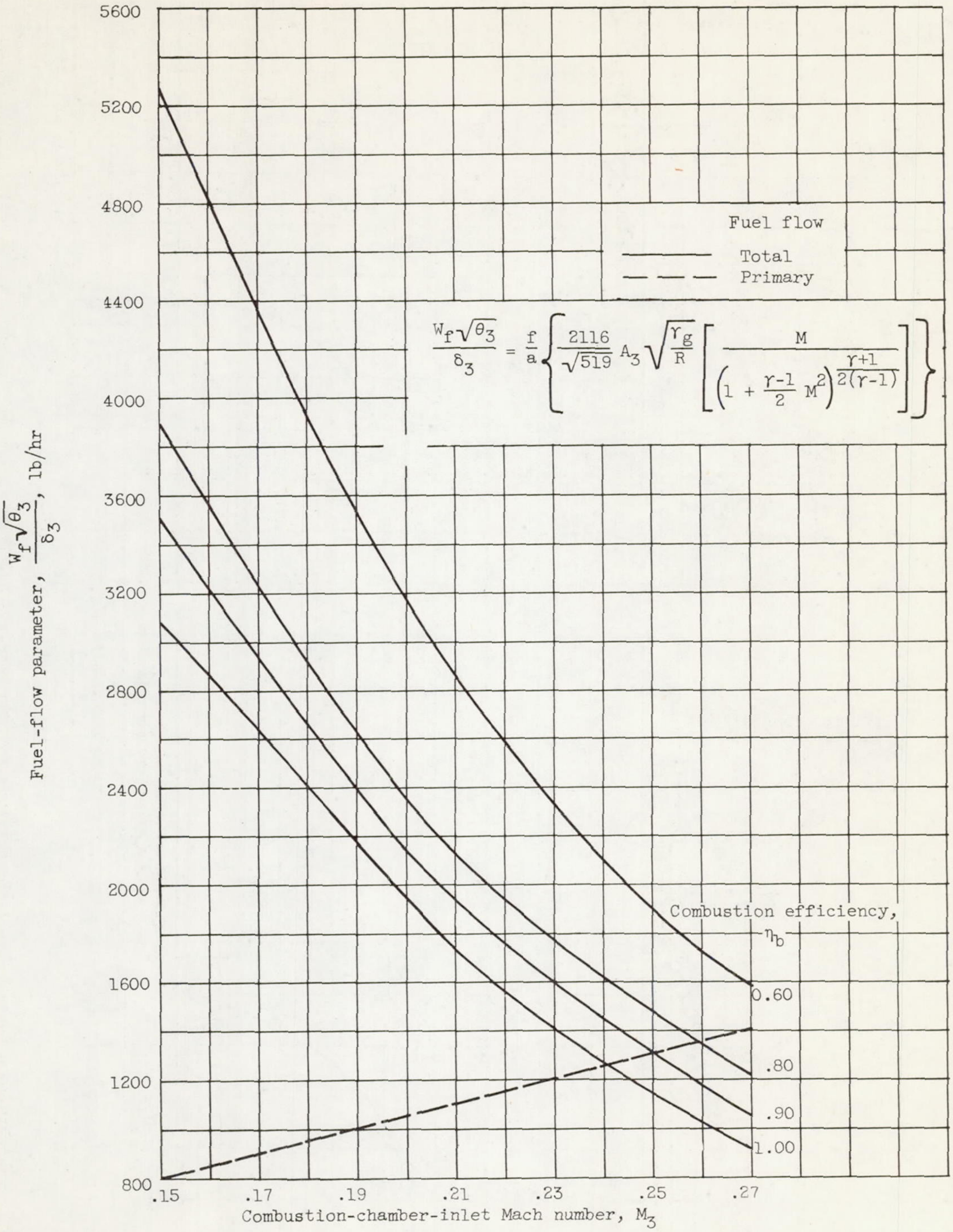

Figure 7. - Engine fuel-flow characteristics. Combustion-chamber-inlet area, 1.168 square feet; flame-holder pressure-loss coefficient, 2.3.

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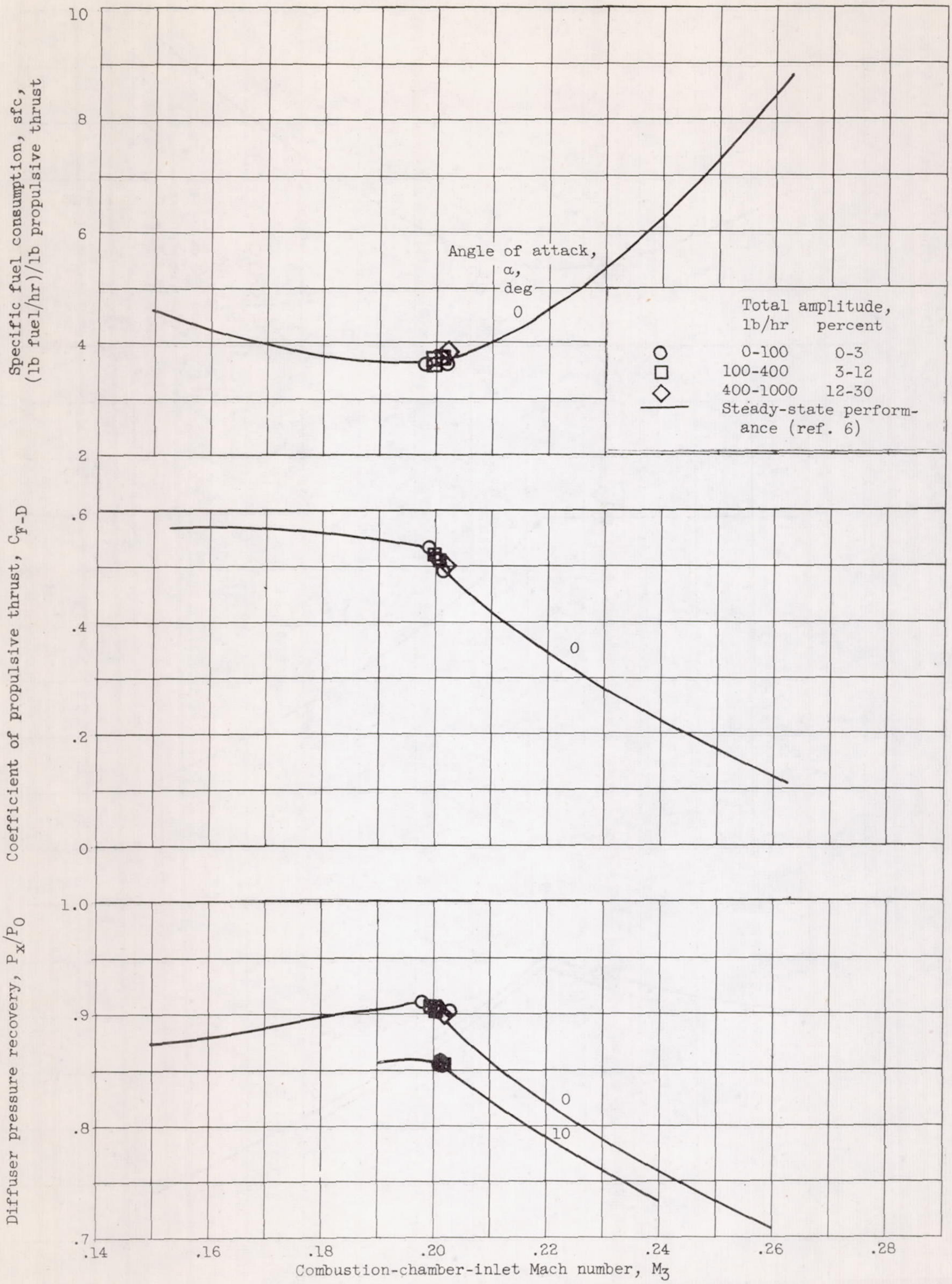
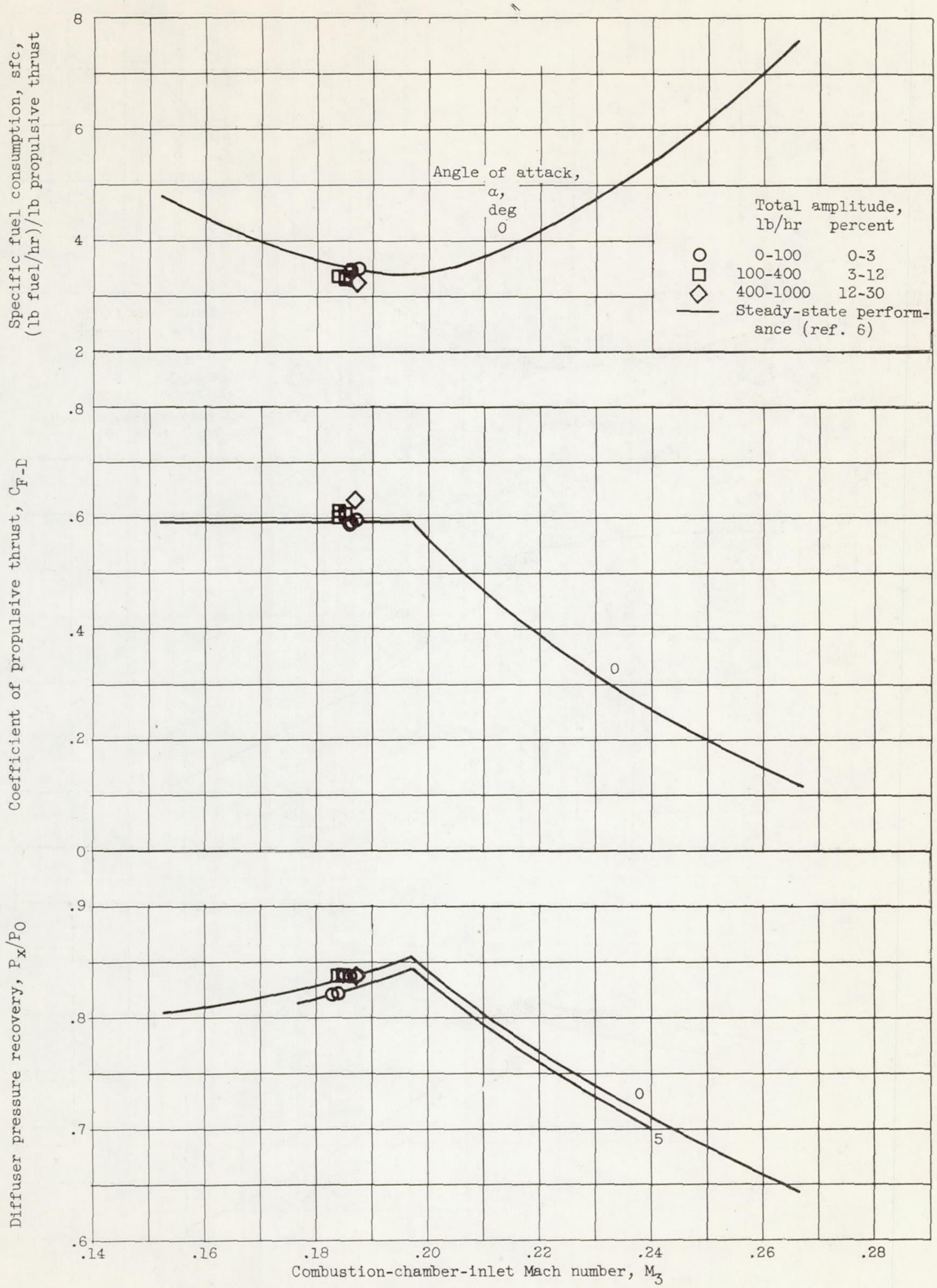


(a) Free-stream Mach number M_0, 1.79.

Figure 8. - Steady-state performance set by control.



(b) Free-stream Mach number M_0, 1.98.

Figure 8. - Continued. Steady-state performance set by control.

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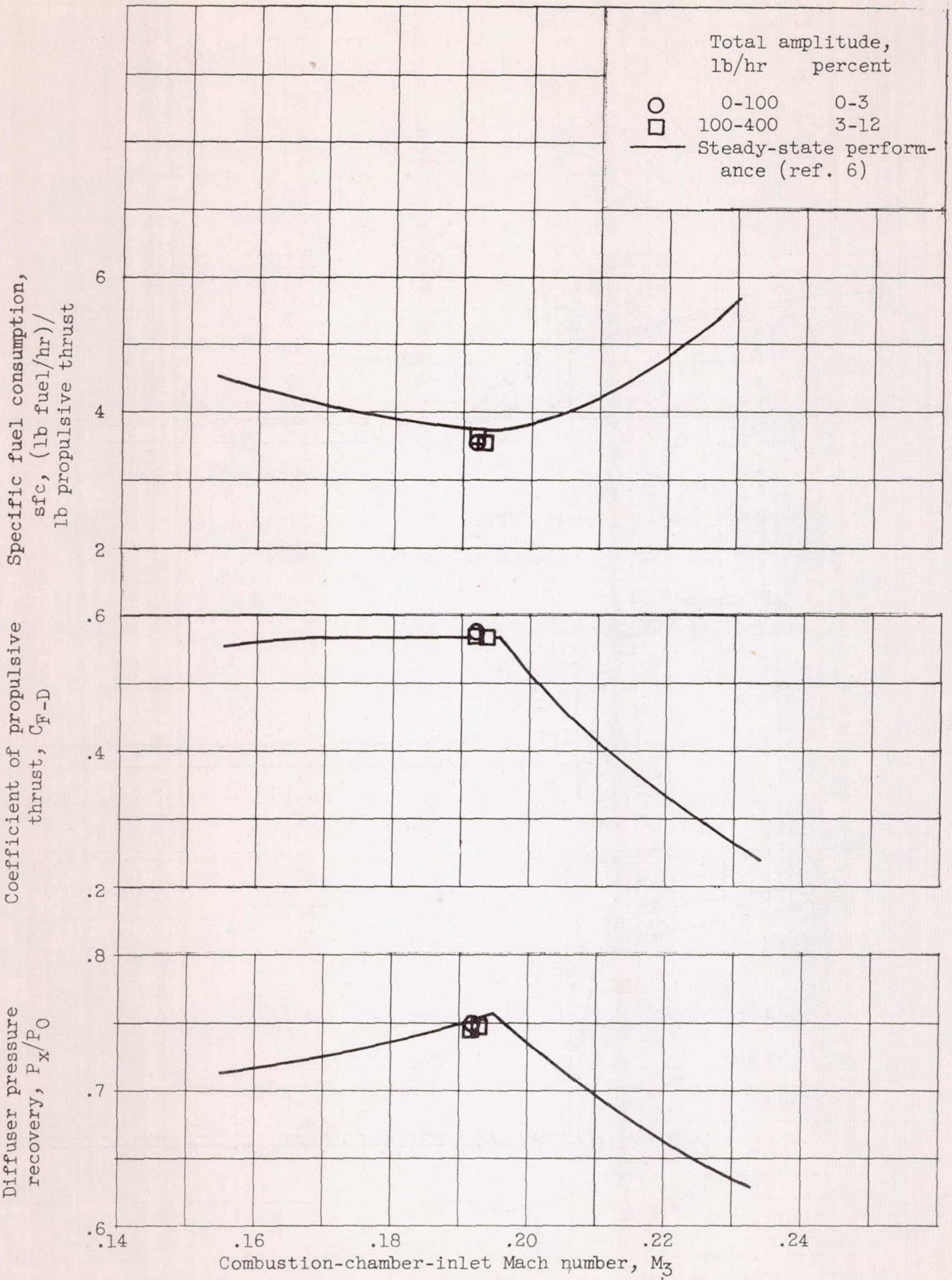
CE-4 back



(c) Free-stream Mach number M_0, 2.16. Zero angle of attack.

Figure 8. - Concluded. Steady-state performance set by control.

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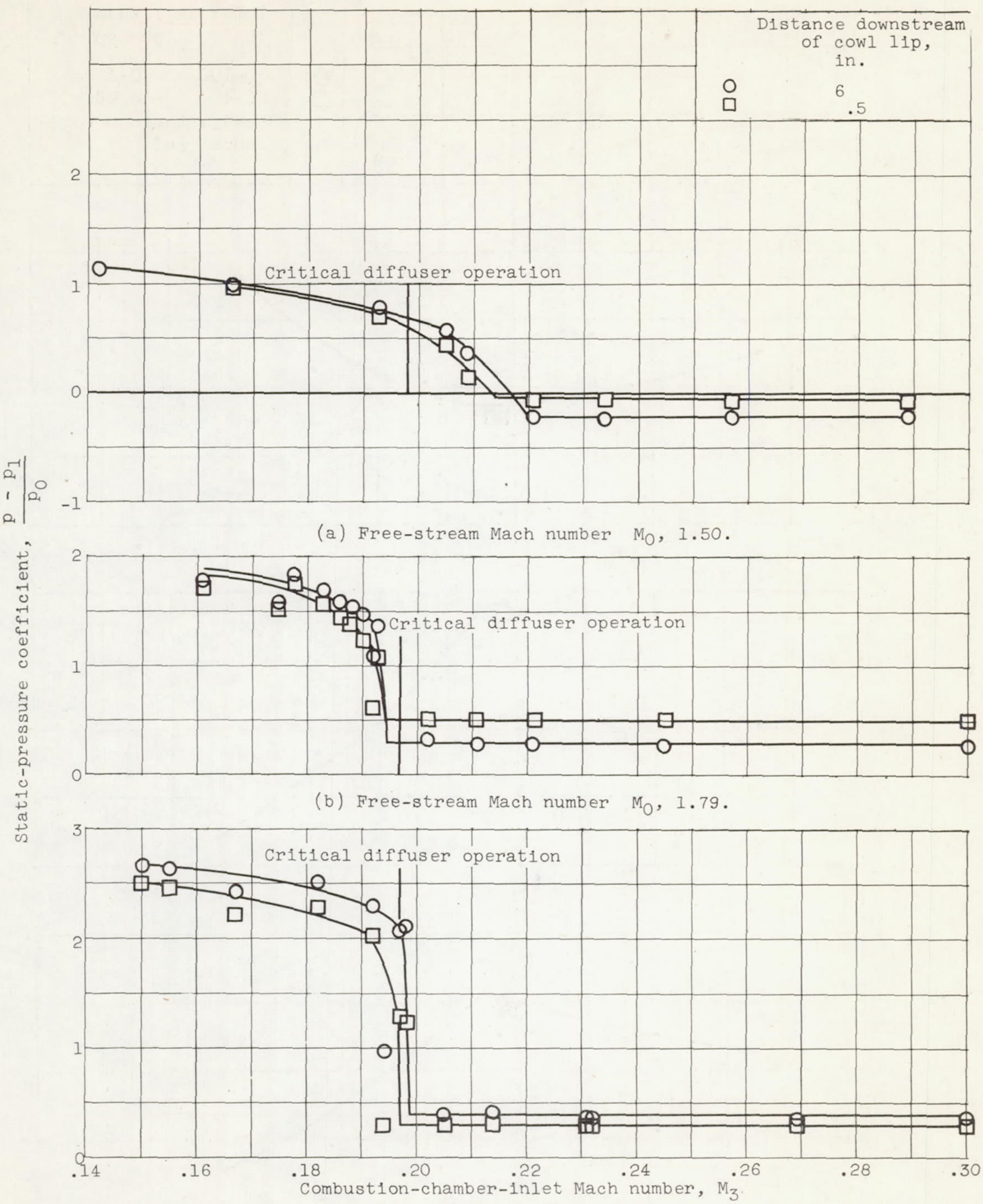

(c) Free-stream Mach number M_0, 1.98.

Figure 9. - Sensing pressures on inside of cowl. Zero angle of attack; zero angle of yaw.

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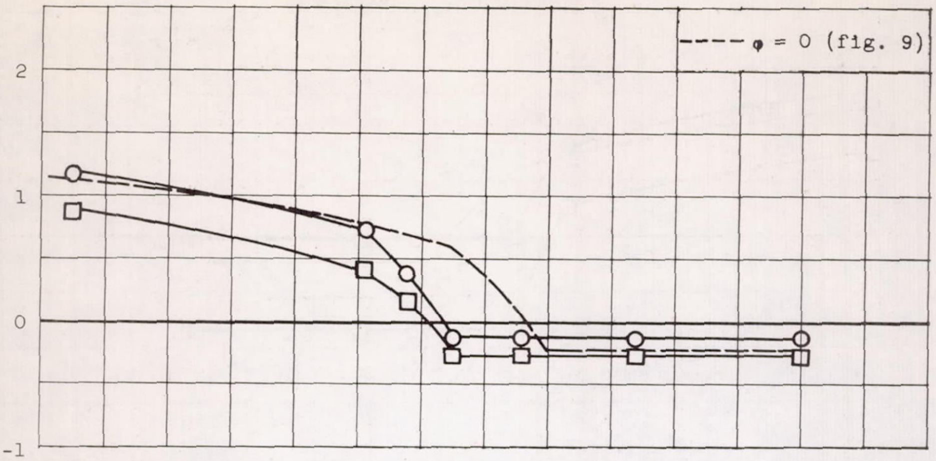
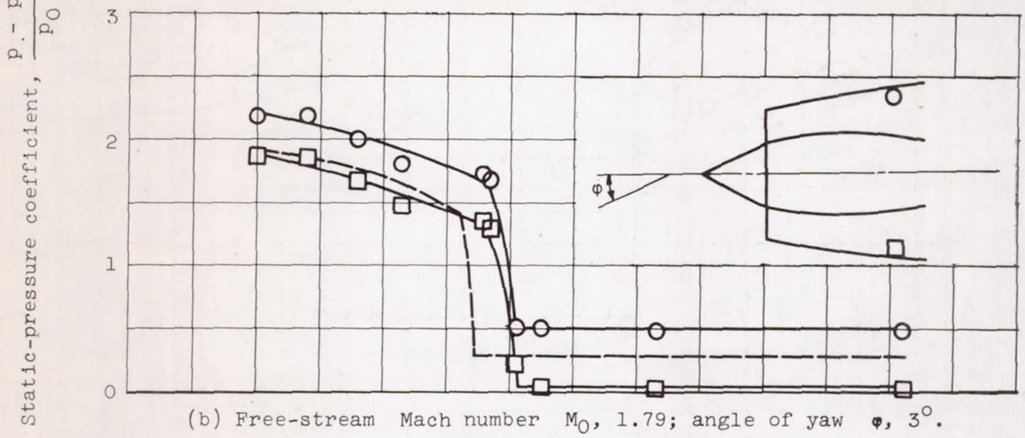
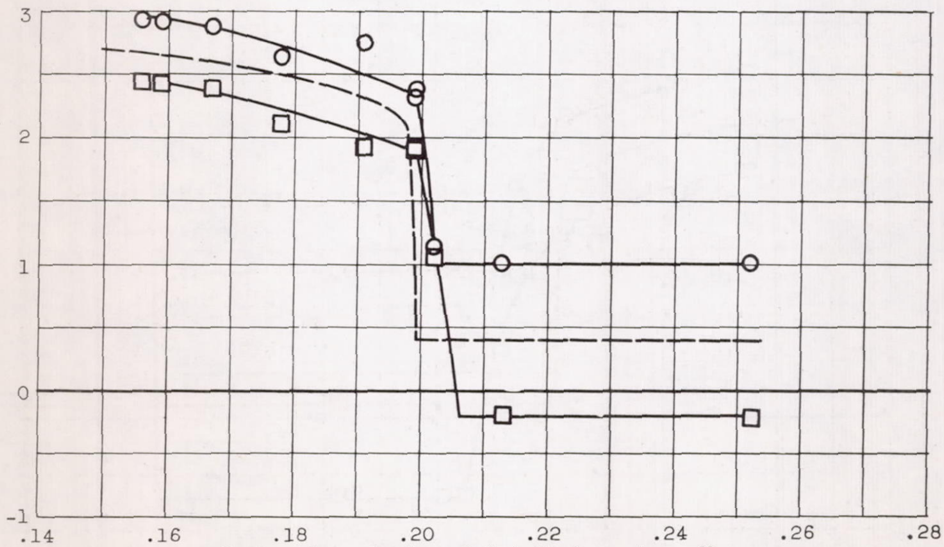


(a) Free-stream Mach number M_0, 1.50; angle of yaw φ, 3°.

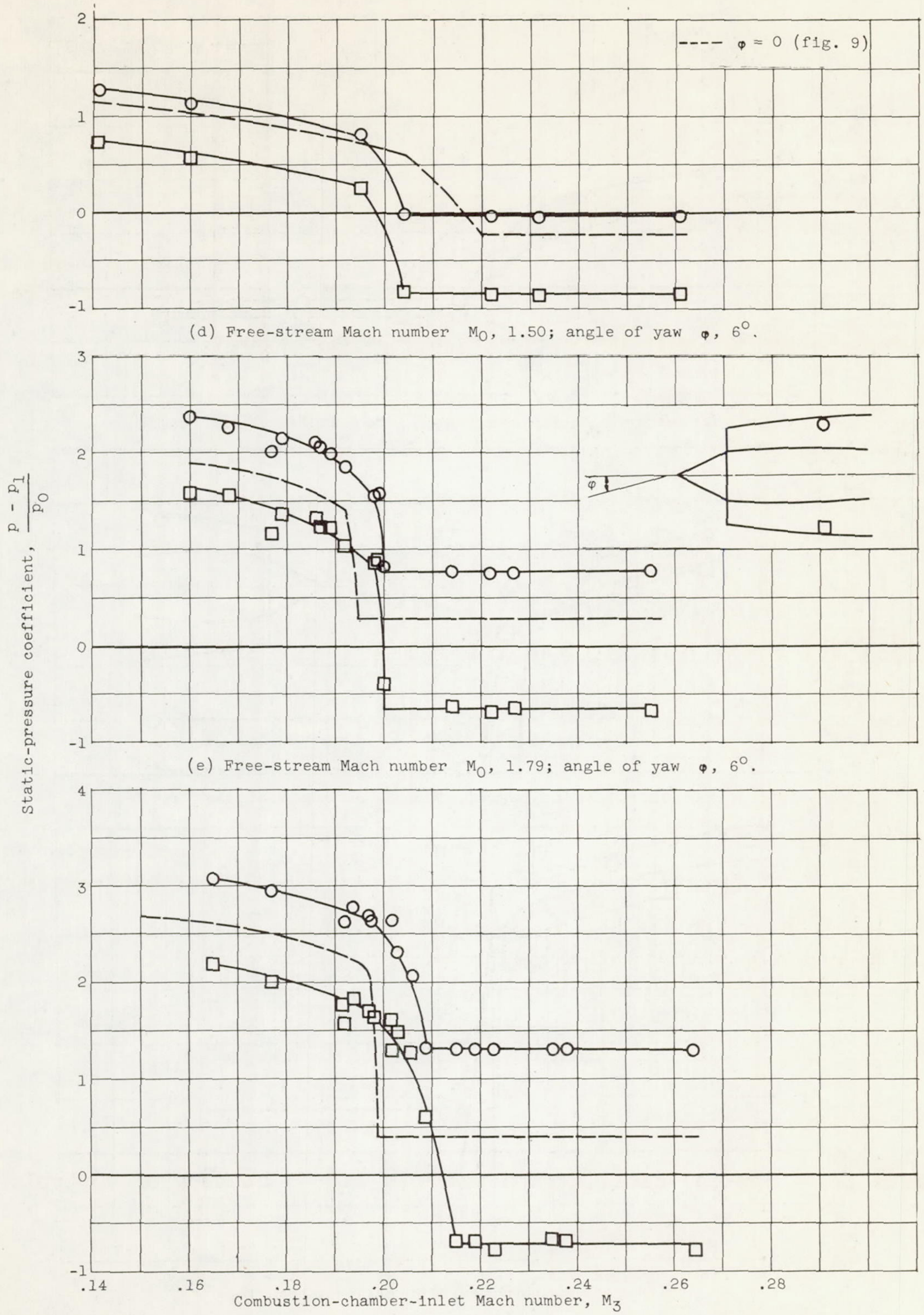


(b) Free-stream Mach number M_0, 1.79; angle of yaw φ, 3°.



(c) Free-stream Mach number M_0, 1.98; angle of yaw φ, 3°.

Figure 10. - Effect of angle of yaw on cowl sensing pressures. Zero angle of attack.



(d) Free-stream Mach number M_0, 1.50; angle of yaw φ, 6°.

(e) Free-stream Mach number M_0, 1.79; angle of yaw φ, 6°.

(f) Free-stream Mach number M_0, 1.98; angle of yaw φ, 6°.

Figure 10. - Concluded. Effect of angle of yaw on cowl sensing pressures. Zero angle of attack.

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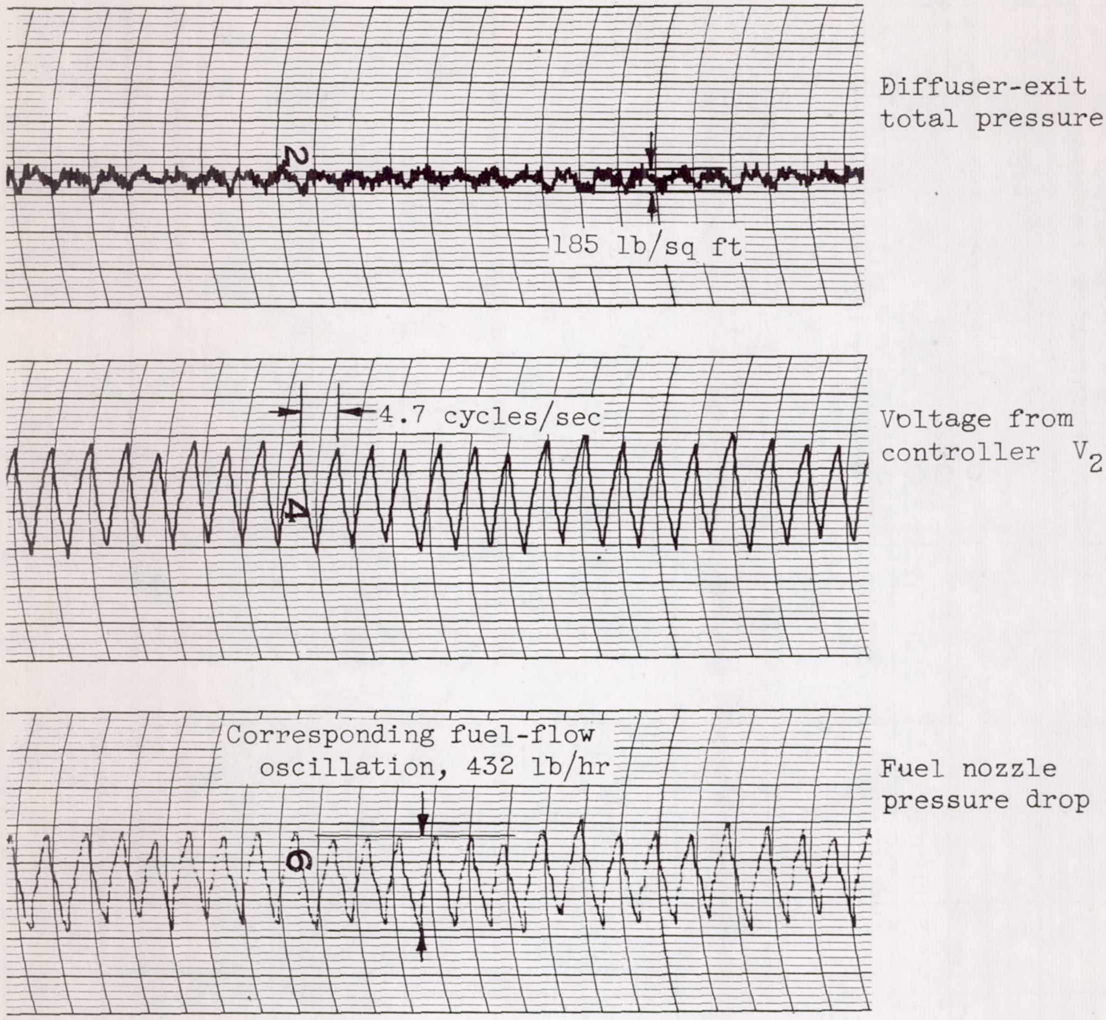

Figure 11. - Typical oscillograph trace of steady hunting of control.

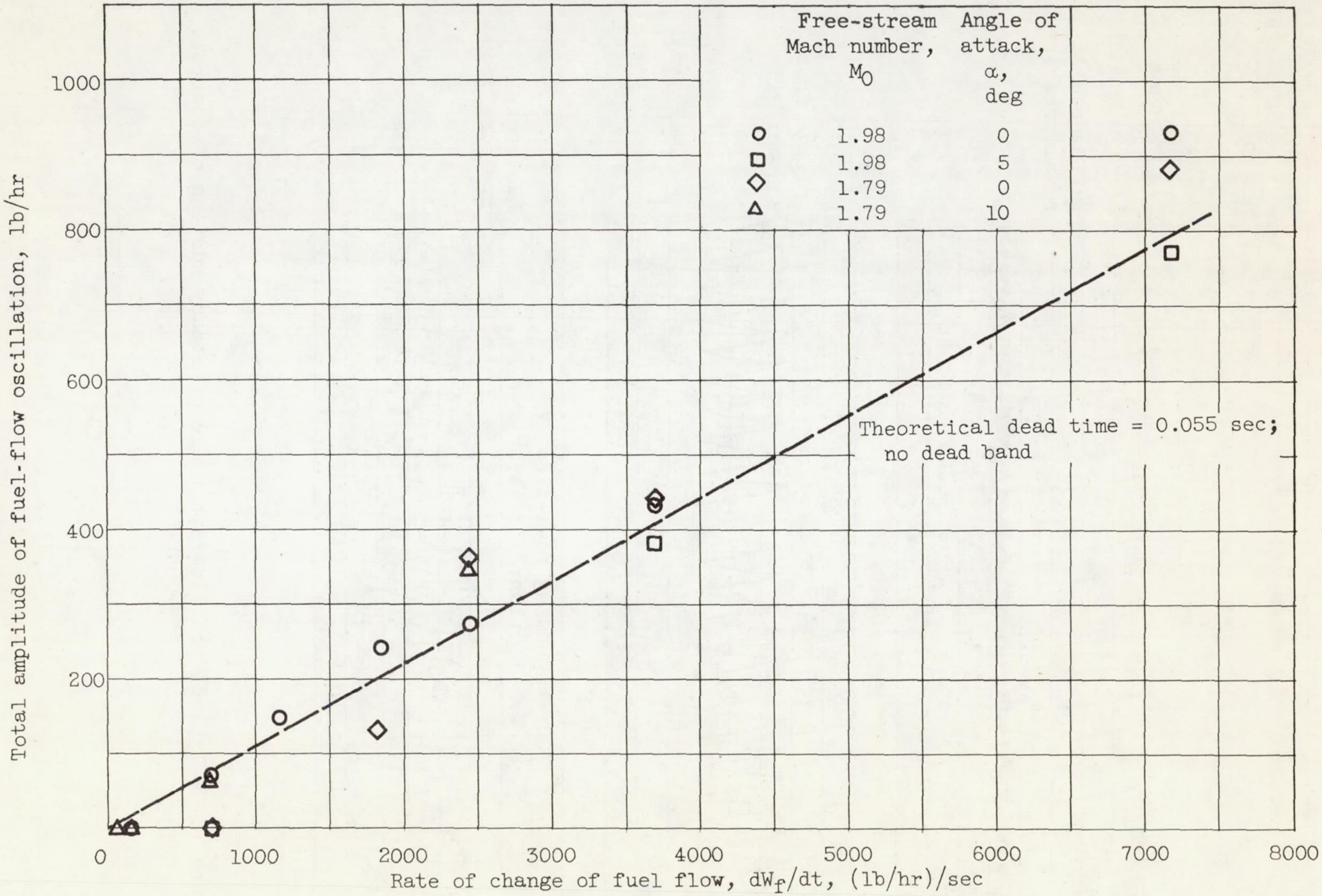

Figure 12. - Oscillation amplitudes for steady hunting operation.

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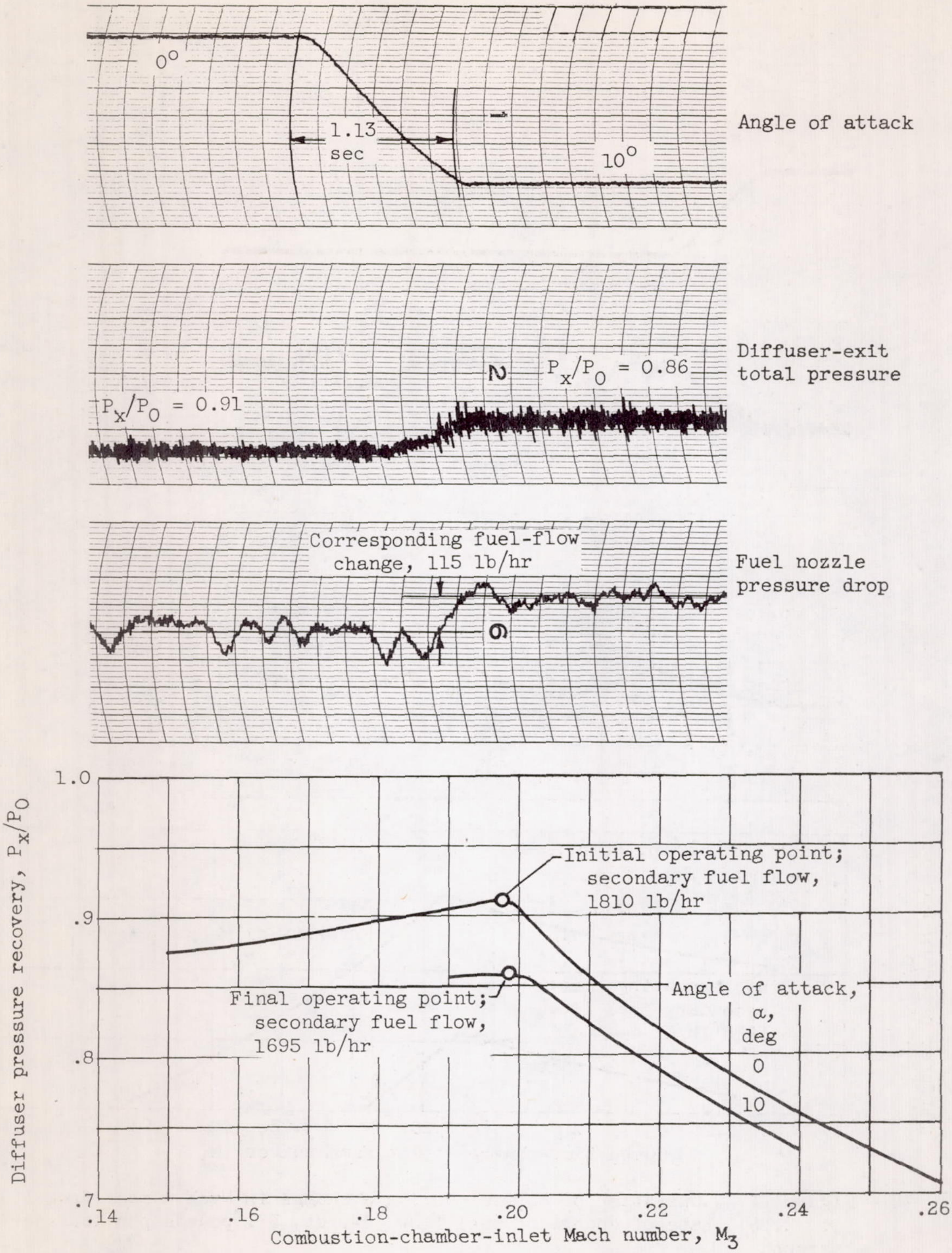

Figure 13. - Operation of control during a change in angle of attack from zero to 10° at Mach 1.79. Rate of change of fuel flow dW_f/dt, 742 pounds per hour per second.

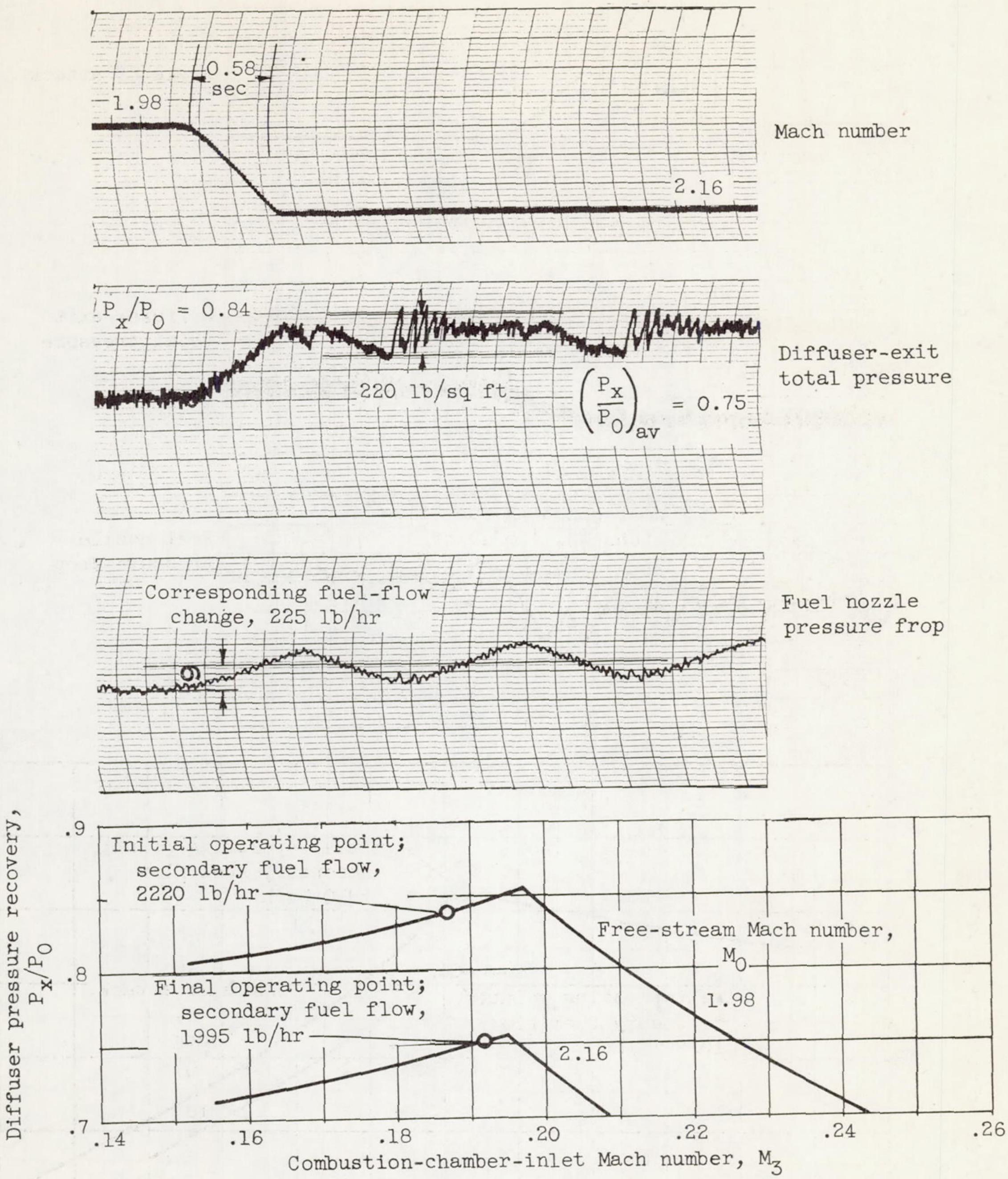

Figure 14. - Operation of control during a change in Mach number from 1.98 to 2.16. Rate of change of fuel flow dW_f/dt, 371 pounds per hour per second.

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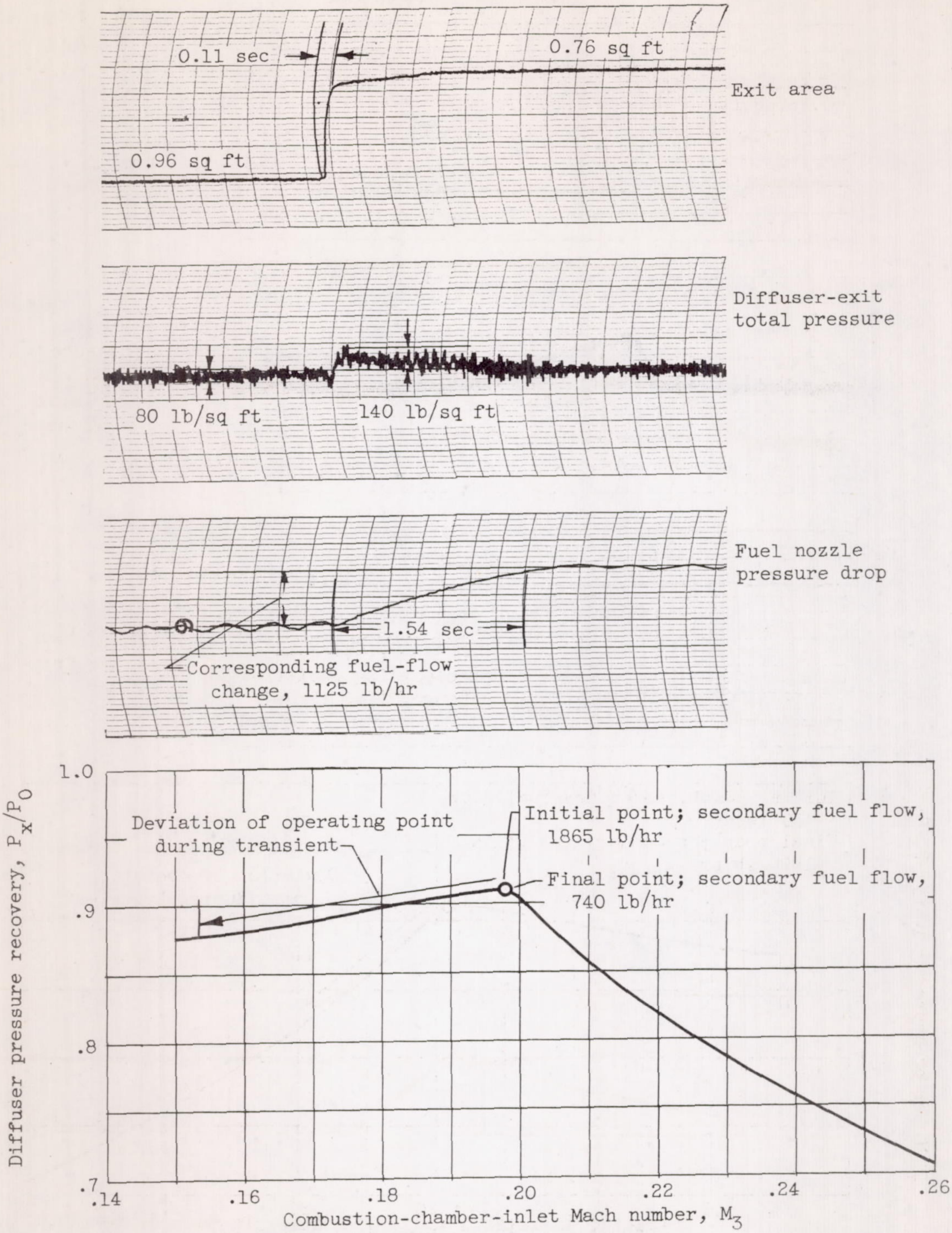
CE-5 back



(a) Initial area, 0.96 square foot; final area, 0.76 square foot; rate of change of fuel flow dW_f/dt, 742 pounds per hour per second.

Figure 15. - Operation of control during change in exit nozzle area at Mach 1.79.

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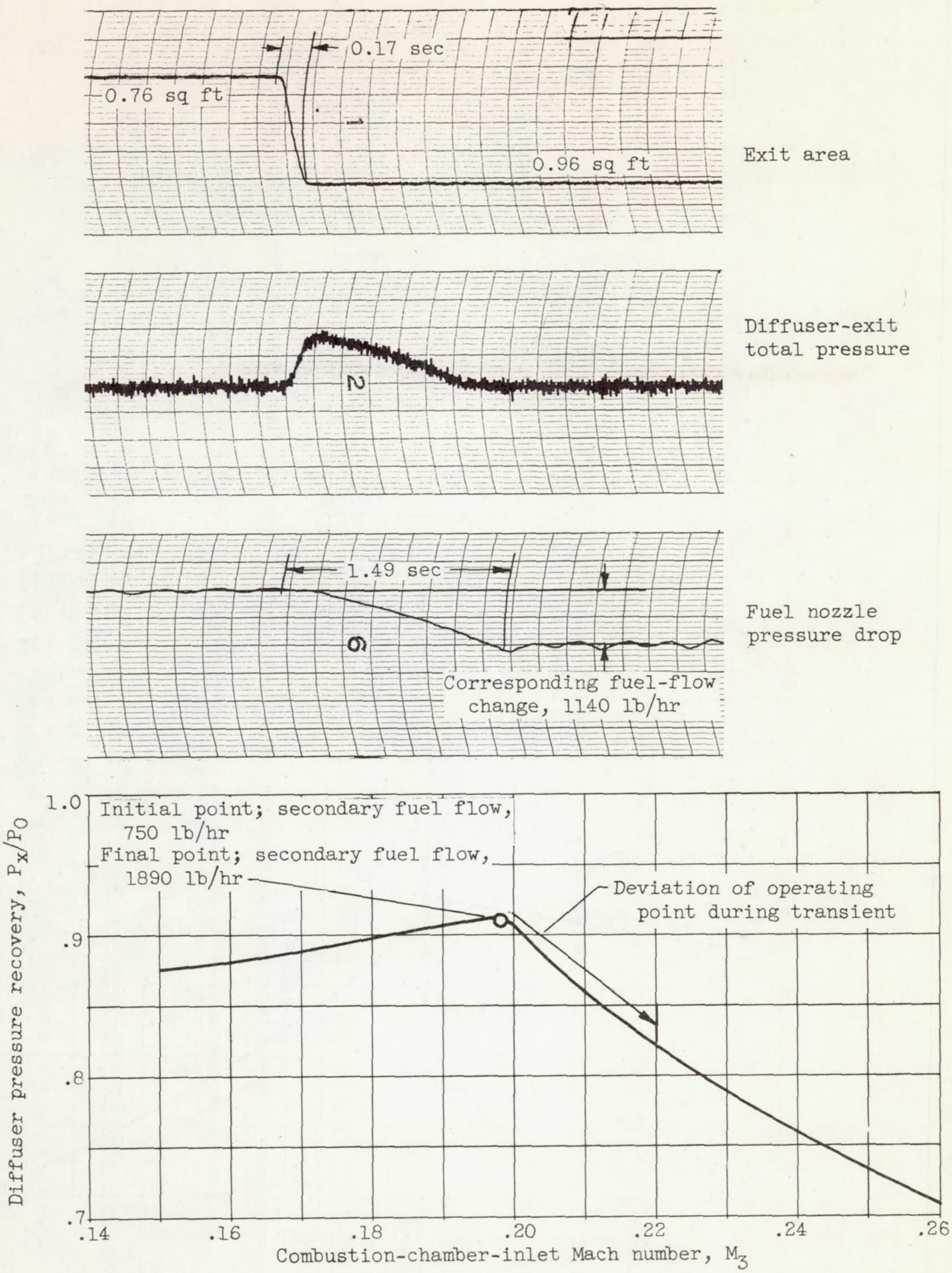

(b) Initial area, 0.76 square foot; final area, 0.96 square foot; rate of change of fuel flow dW_f/dt, 742 pounds per hour per second.

Figure 15. - Continued. Operation of control during change in exit nozzle area at Mach 1.79.

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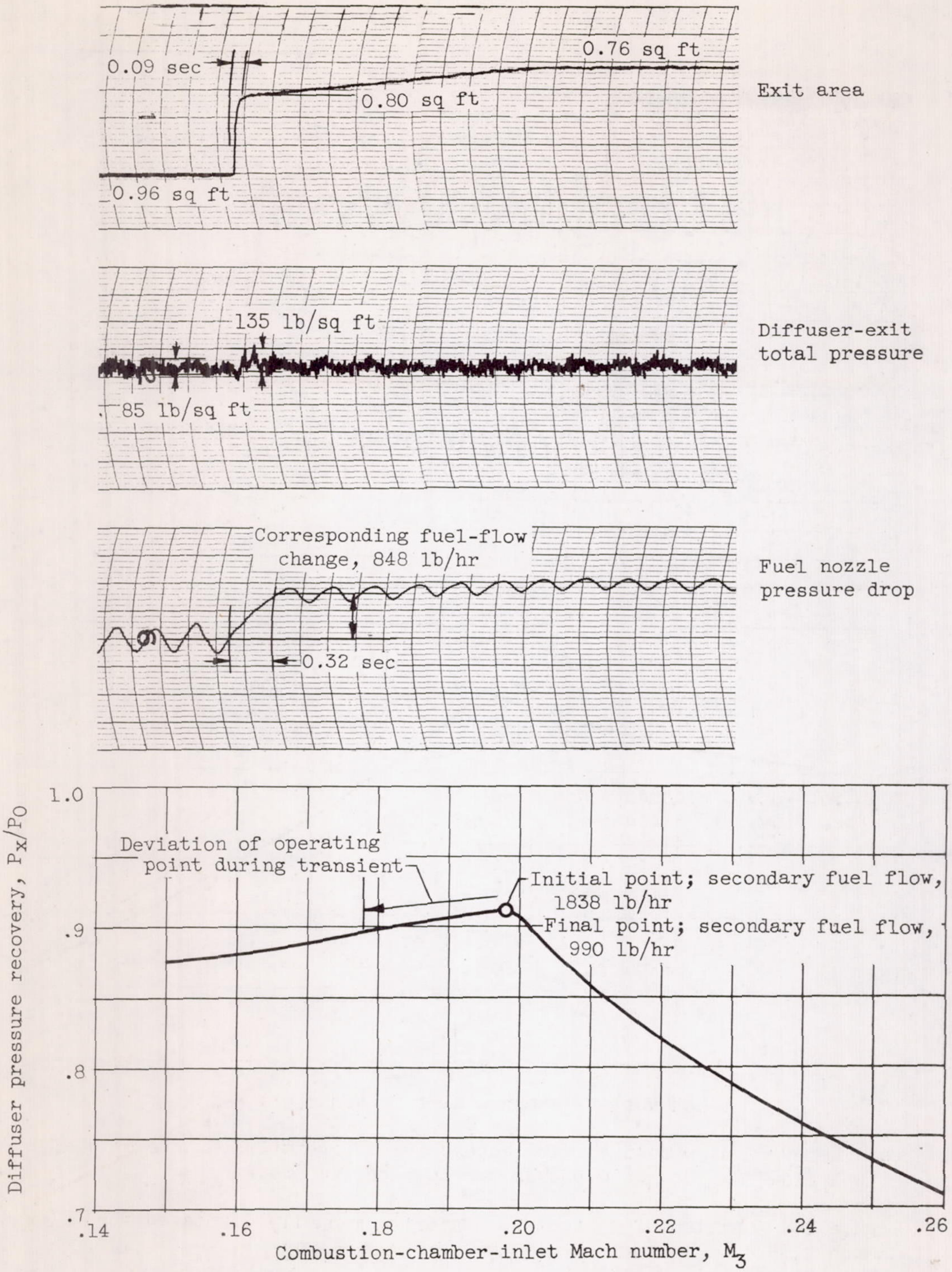
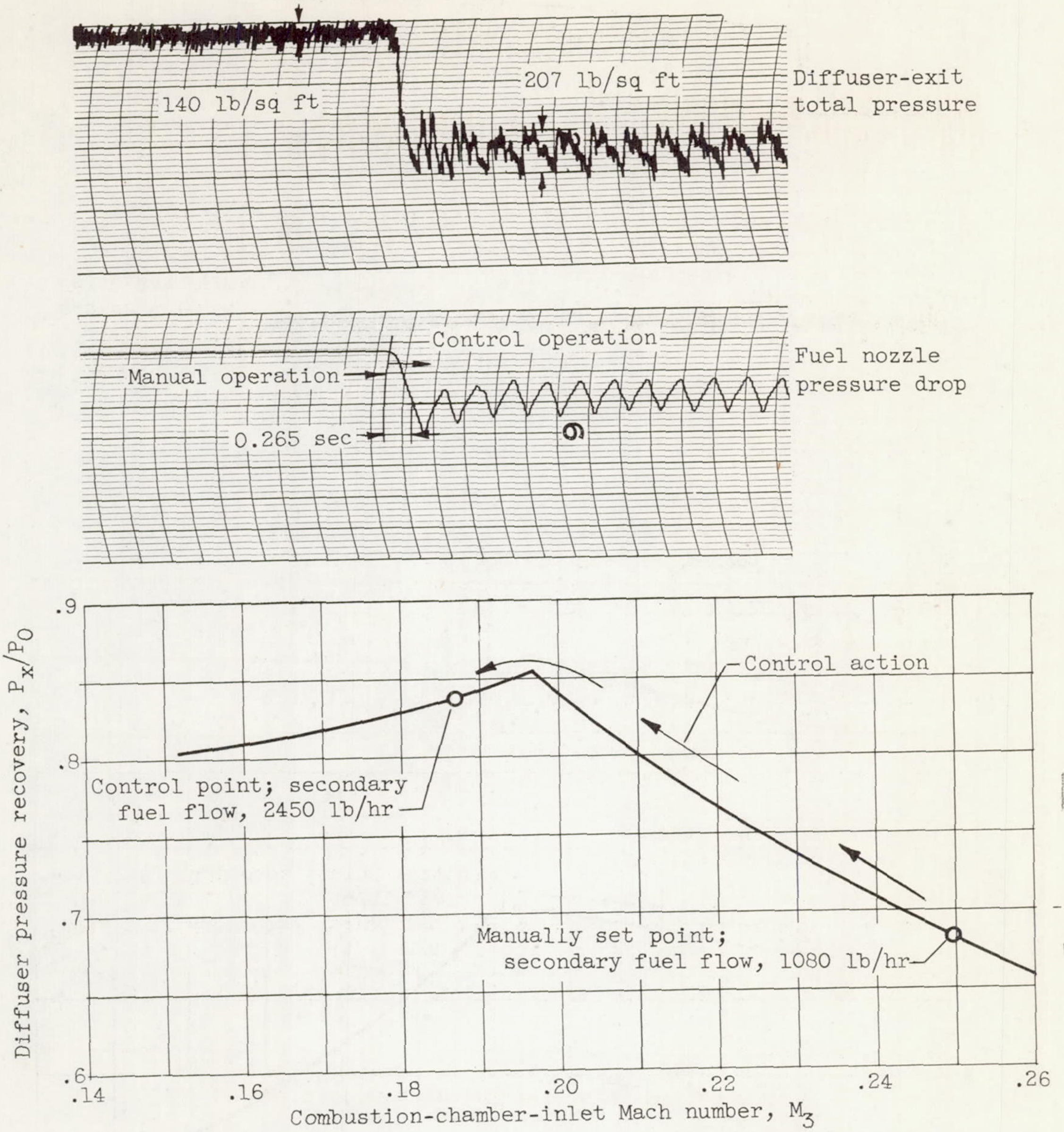


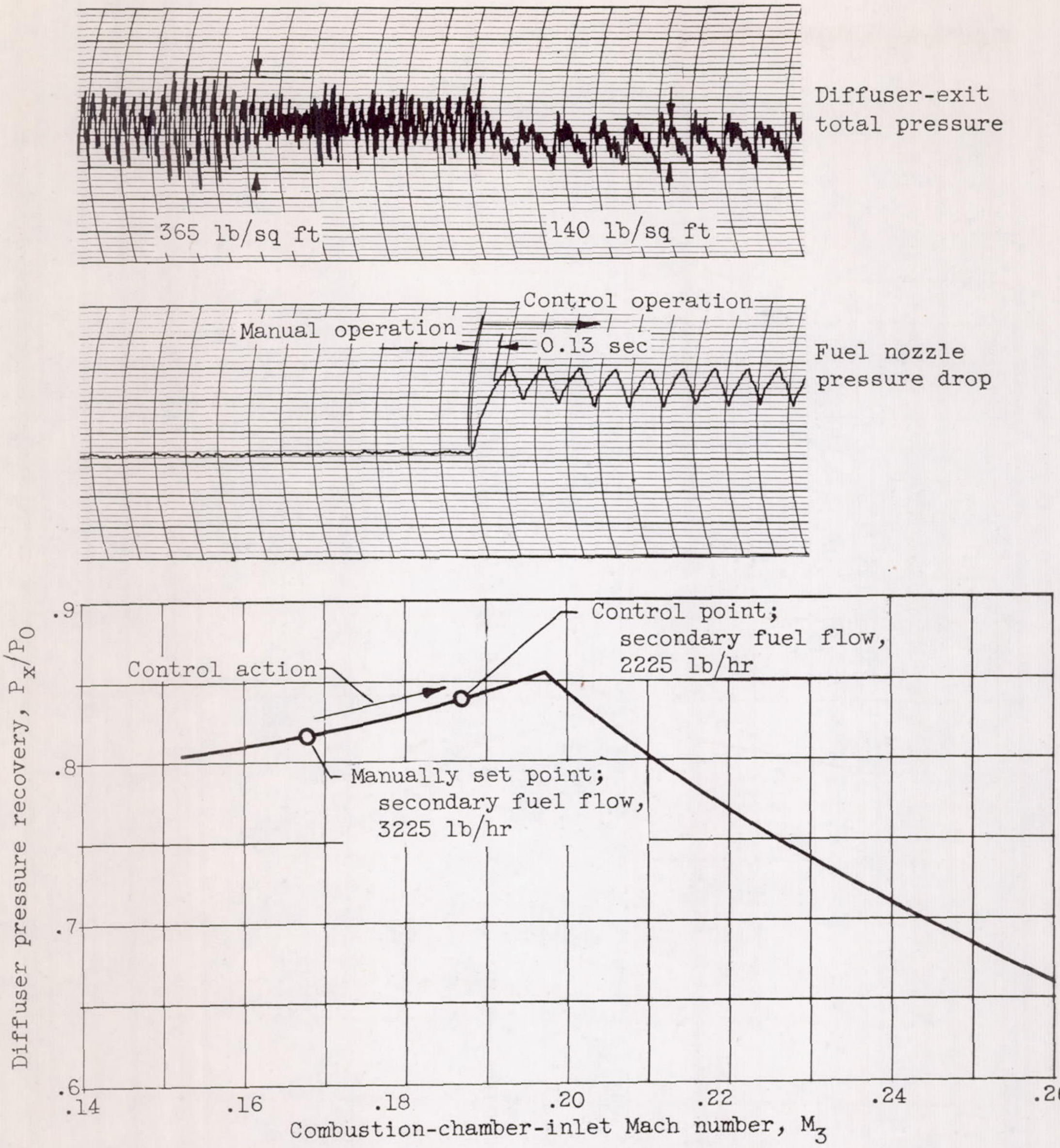
(c) Initial area, 0.96 square foot; final area, 0.80 square foot; rate of change of fuel flow dW_f/dt, 2450 pounds per hour per second.

Figure 15. - Concluded. Operation of control during change in exit nozzle area at Mach 1.79.



(a) Fuel flow displaced to give supercritical operation. Rate of change of fuel flow dW_f/dt, 7150 pounds per hour per second.

Figure 16. - Action of control in restoring manually displaced fuel flow at Mach 1.98.



(b) Fuel flow displaced to give diffuser buzz. Rate of change of fuel flow dW_f/dt, 7150 pounds per hour per second.

Figure 16. - Concluded. Action of control in restoring manually displaced fuel flow at Mach 1.98.

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